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**Soil
Conservation
Service**

National
Engineering
Handbook

Section 15

Irrigation

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Chapter 1

Soil-Plant-Water Relationships

Chapter 1
Soil-Plant-Water Relationships

Contents

Page

Figures iii
Tables v
Nomenclature vi
Preface vii
Introduction 1-1

Soil 1-3
- Soil Physical Properties 1-3
- Soil Texture 1-3
  - Mineral Soil 1-3
  - Organic Soil 1-5
- Soil Structure 1-5
- Tilth 1-5
- Soil Porosity 1-6
- Soil Compaction 1-7
- Soil Salinity and Sodicity 1-7
- Categories of Salt-Affected Soils 1-7
- Soil Water 1-8
  - Soil Water Potential 1-8
  - Soil Water Characteristic Curves 1-10
  - Water Movement in Soil 1-10
  - Plant Available Water 1-12
  - Soil Water Measurement 1-14
  - Methods Used for Characterizing Soil Water 1-14
    - Gravimetric 1-15
    - Feel and Appearance Method 1-15
    - Tensiometers 1-17
    - Electrical-Resistance Instruments 1-18
    - Neutron Scattering 1-19
    - Heat Dissipation 1-19
  - Sampling Error 1-19
  - Location of Soil Water Measurements 1-20

Water Intake 1-21
- Percolation 1-21
- Factors Affecting Infiltration 1-21
  - Soil Water Content 1-21
  - Soil Sealing 1-21
  - Surging 1-22
  - Compaction 1-22
  - Tillage 1-22
  - Soil Cracking 1-22
  - Organic Material 1-22
  - Salts in Soil 1-22
  - Sediments in Irrigation Water 1-23
  - Soil Erosion 1-23
  - Land Leveling 1-23
  - Temperature 1-23
  - Surface Storage 1-23

Infiltration Stages 1-23
Cumulative Infiltration and Infiltration Rate Relations 1-24
Basic or Steady Infiltration Rate 1-24
Seasonal and Spatial Variation 1-24
Field Infiltration Measurements 1-25
Models 1-27
Plants 1-28
Plant Root Systems 1-28
Crop Species Rooting Characteristics 1-28
Factors Affecting Root Growth 1-30
Water Flow Into Roots 1-30
Water Uptake-Root Profile Relations 1-30
Plant Water Use from Shallow Water Tables 1-31
Design Water-Extraction Depth 1-32
Evapotranspiration (ET) 1-32
Potential ET 1-32
Predicting Crop ET 1-34
Crop Coefficient 1-35
Crop Critical Stress Periods 1-37
Yield-Evapotranspiration Relationships 1-38
Concepts of Production Functions 1-38
Yield-Evapotranspiration Production Functions 1-39
Yield-Applied Water Relationships 1-39
Transferability of Yield-Evapotranspiration Functions 1-40
Salinity Effects 1-41
Plant Factors 1-44
Soil Factors 1-44
Climatic Factors 1-44
Specific Ion Effects 1-44
Acid Soils 1-45
Chemistry of Acid Soils 1-45
Effects of Soil Acidity on Plant Growth 1-45
Crop Response to Liming in the United States 1-45
Determining Lime Requirement 1-46
Scheduling Irrigations 1-49
Water Balance 1-49
Allowable Water Depletion 1-49
Soil Water Extraction Depth 1-50
Net Water Calculations 1-50
Water Balance Accounting Procedures 1-51
Plant Based Concepts 1-52
Pressure Chamber 1-52
Leaf or Canopy Temperature Methods 1-53
Visual Appearance 1-54
Indicator Plants 1-54
Automation in Irrigation Scheduling 1-56

Figures

1-1.—Four climatic areas in the United States: arid, semiarid, subhumid, and humid (AAVIM Planning for an Irrigation System, 2nd edition, 1980) 1-2

1-2.—Proportions of sand, silt, and clay in basic soil textural classes 1-4

1-3.—Types of soil structure and their effect on downward movement of water (U.S. Dept. Agr. and U.S. Dept. of Int. Agr. Inf. Handbook 199. Irrigation on Western Farms, 53 pp., illus. 1959) 1-6

1-4.—Effect of soil bulk density on alfalfa root growth in greenhouse pots at the end of 80 and 110 days (D.W. Grimes, W. R. Sheesley, and P. L. Wiley, 1978. Agron. J. 70:955-958) 1-8

1-5.—Illustrations and example calculations for gravitational, matric, and pressure potential based on weight as specifying the unit of water. Increasing depth below the soil surface is considered to be negative in the illustrations (R. J. Hanks and G. L. Ashcroft, 1980. Applied Soil Physics. Springer-Verlag, Berlin) 1-10

1-6.—Soil water characteristic curves (M. D. Thorne and W. A. Raney. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6, 14 pp., illus. 1956) 1-11

1-7.—Water penetration and movement in sandy and clay loam soils; to achieve complete wetting, furrows have to be closer together on sandy soils 1-13

1-8.—Relation between the water content and the water tension of a soil 1-14

1-9.—General relationship between soil water characteristics and texture (adapted from The Nature and Properties of Soils, Nyle C. Brady, 1984) 1-14

1-10.—Water release curve for three soils (M. D. Thorne and W. A. Raney, 1956. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6, 14 pp.) 1-15

1-11.—Soil water depletion by cotton on a Panoche clay loam (D. W. Grimes, 1986. Texas Agr. Exp. Sta. MP-1616) 1-16

1-12.—Tensiometers are used to measure soil water at a point in the soil profile 1-17

1-13.—Electrical resistance soil water meters 1-18

1-14.—Predicted infiltration rates for a deep Columbia silt loam with different initial water contents (ASAE Monograph, Farm Irrigation Systems, 1980) 1-21

1-15.—Potential runoff for high and low steady water application rates similar to stationary sprinklers (ASAE Monograph, Farm Irrigation Systems, 1980) 1-23

1-16.—Potential runoff for nonstationary sprinkler 1-24

1-17.—Relation of cumulative infiltration to time for three soils 1-25

1-18.—Relation of infiltration rate to time for three soils 1-26

1-19.—Fibrous root system of corn (left) and taproot system of sugar beet (right): both are approximately two months old (R. Scott Russell, 1977. Plant root system. McGraw-Hill, U.K. p. 51 and John E. Weaver and Frederic E. Clements, 1938. Plant Ecology. McGraw-Hill, New York and London, p. 313) 1-28

1-20.—Average water extraction pattern of plants growing in a soil without restrictive layers and with an adequate supply of available water throughout the root zone 1-31

1-21.—Water extraction patterns as determined by available water content in various parts of soil profile. Width of each profile represents total available water; gross area (height and width) of each profile represents total available water in profile; hatched area shows water extraction pattern for each profile [Dale R. Shockley, 1955. Capacity of soil to hold moisture. Agri. Engin. 36(2):109-112] 1-32

1-22.—Upward flux-water table depth relationships for eight North Carolina soils (W. Skaggs, 1980. Drainmod. USDA-SCS Reference Report) 1-33

1-23.—Change in relative rooting depth with relative time for annual crops (H. Borg and D. W. Grimes, 1986. Transactions of the ASAE 29:194-197) 1-34

1-24a through 1-24f.—Monthly reference estimates from several different procedures versus lysimeter-measured ET (ASCE Water Requirements Committee, 1987) 1-36

1-25.—Illustration of a crop coefficient curve (J. Doorenbos and W. O. Pruitt, 1977. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper No. 24, p. 144) 1-38

1-26.—Alfalfa hay yield-ET and yield applied water (AW) functions for the San Joaquin Valley, California (D. W. Grimes, personal communication) 1-39

1-27.—Cotton lint yield-ET and lint yield-applied water (AW) functions for the San Joaquin Valley, California (D. W. Grimes and Kamal Elzik, 1982. Cotton water management. University of California Bull. No. 1904) 1-39

1-28.—Relative yield of Thompson grapes versus relative evapotranspiration (L. E. Williams and D. W. Grimes, 1987. Modeling vine growth-development of a data set for a water balance subroutine. Sixth Australian Wine Industry Tech. Conf., Adelaide) 1-40

1-29.— Nutrient Availability in Acid Soils: the wider the bar, the more available is the nutrient (adapted from Emil Truog, USDA Yearbook of Agriculture, 1943-47) 1-46

1-30.—Components of a field water balance (E. Fereres, D. W. Henderson, W. O. Pruitt, W. F. Richardson, and R. S. Ayers, 1981. Basic irrigation scheduling. Div. of Agricultural Sciences University of California Leaflet 21199, 8 pp.) 1-49

1-31.—Generalized relationship between soil-water retention and crop growth 1-50

1-32.—Diurnal leaf water potential curves for cotton of contrasting water stress levels (D. W. Grimes and H. Yamada, 1982. Relation of cotton growth and yield to minimum leaf water potential. Crop Sci. 22:134-139) 1-53

1-33.—Foliage-air temperature differential versus air vapor pressure deficit for well-watered alfalfa grown at a variety of specific sites and dates (S. B. Idso, R. D. Jackson, R. J. Pinter, Jr., R. S. Reginato, and J. L. Hatfield, 1981. Normalizing the stress-degree day parameter for environmental variability. Agric. Meteorol. 24:24-55) 1-55

Tables

1-1.—Range in particle size by texture 1-3

1-2.—General terms for basic soil textural classes (U.S. Dept. of Agr. Soil Survey Manual, 430-V. June 9, 1981) 1-5

1-3.—Classification of salt-affected soils 1-9

1-4.—Ranges in available water content by soil textural classes 1-13

1-5.—Data source summary of several crop species on the depth development of roots with time and expected maximum rooting depth (RD_m) under favorable environmental conditions (H. Borg and D. W. Grimes, 1986. Depth development of roots with time on empirical description.Transactions of the ASAE. Vol. 29, No. 1, pp. 194-197) 1-28

1-6.—General factors for conversion from one method of estimating crop ET to another (Snyder & Dickey, 1982) 1-35

1-7.—Critical periods for water stress, symptoms, and some other considerations for several important crops 1-37

1-8.—Salt tolerance of herbaceous crops (E. V. Maas, 1986. Applied Agricultural Research 1:12-26) 1-42

1-9.—Tolerance classification of plants to boron (Robert S. Ayers, 1977. Quality of water for irrigation. J. Irrig. Drain. Div. ASCE, IR2, 103:135-154) 1-44

1-10.—Permissible soil pH ranges for various crops growing on mineral soils in Michigan (C.M. Woodruff, 1967. In Soil, Acidity and Liming. Robert W. Pearson and Fred A. Adams, eds. Agronomy Monograph No. 12. Amer. Soc. Agron. Madison, WI, p. 222) 1-47

1-11.— Approximate amounts of finely ground limestone needed to raise the pH of a 7-inch layer of soil 1-48

1-12.—Suggested percentage of available soil water content remaining in the crop root zone when an irrigation should be scheduled for several common crops 1-50

1-13.—Water retention characteristics of a Hinckley loamy sand 1-51

1-14.—Example of water balance accounting procedure 1-52

Nomenclature

AW = Applied water in inches

AWC = Available water capacity of a soil. Water content difference between FC and PWP

B.D. = Bulk density of soil in grams per cubic centimeter

C_{et} = Coefficient to convert ET_p to ET_c

C,S,b = Infiltration function parameters related to soil characteristics

CWSI = Crop water stress index

D = Depth of water in soil in inches

d = Soil depth in inches

dw = Density of water as 1 gram per cubic centimeter

E_{pan} = Evaporation from National Weather Service "class A" evaporation pan

EC_e = Electrical conductivity of soil solution saturation extract in decisiemens per meter

ET = Evapotranspiration in inches

ET_a = Actual crop ET

ET_c = Evapotranspiration of a specified crop

ET_m = Maximum crop ET

ET_o = Reference ET (approximates 4-7 inch tall grass)

ET_p = Potential ET (approximates uncut alfalfa)

F = Cumulative infiltration in inches

f = Infiltration rate in inches per hour

FC = Field capacity, the water content a soil will hold when freely drained (1/10 to 1/3 atmosphere tension).

f_c = Final infiltration rate in inches per hour

f_o = Infiltration rate at time 0 in inches per hour

H = Hydraulic head in feet

K = Hydraulic conductivity in feet per day

k_c = Crop coefficient, unitless

K_c = Coefficient to convert ET_o to ET_c

K_p = Coefficient to convert E_{pan} to ET_c

K_{pan} = Coefficient to convert E_{pan} to Et_o

K_s = Saturated hydraulic conductivity in inches per day

k,a = Infiltration function fitting parameters

L = Distance in feet

Md = Difference between initial and final water content

PWP = Permanent wilting point (the water content of a soil at 15 atmospheres tension)

q = Flux density in volume per unit area per time

R = Universal gas constant

RD_m = Maximum rooting depth

SAR = Sodium absorption ratio, unitless

S_f = Suction or matrix potential at the wetting front in inches

T = Absolute temperature in degrees kelvin

t = Time after irrigation starts in hours

T_a = Air temperature in degrees celsius

T_f = Foliage temperature in degrees celsius

Y_a = Actual crop yield associated with ET_a

Y_m = Maximum crop yield associated with ET_m

Preface

Section 15 of the National Engineering Handbook (NEH), Irrigation, supplies engineers and others with the basic data necessary to plan, design, and maintain efficient conservation irrigation practices. Engineering principles and research findings have been screened to give emphasis to the information needed to provide technical assistance to individual farmers and groups of farmers. Chapter 1, Soil-Plant-Water Relationships, describes those properties of soils and plants that affect the movement, retention, and use of water that are essential to plant growth.

The first edition of this chapter was published in March 1964. This updated second edition was prepared by Dr. Wes Wallender and Dr. Don Grimes of the University of California at Davis under contract to the Soil Conservation Service (SCS). The principal reviewers of this publication for SCS were Paul K. Koluvek, retired, Gylan L. Dickey, Carroll A. Hackbart, and Elwin A. Ross, National Technical Center irrigation engineers, and Swayne F. Scott, national irrigation engineer, retired. Valuable comment also was provided by Bobby Birdwell, assistant director of the Soils Division, retired; Milton W. Meyer, soil characterization specialist; and David L. Schertz, national agronomist. Final review was provided by Richard Van Klaveren, national irrigation engineer.

NEH Section 15, Chapter 1 is written for the employees of the Soil Conservation Service who provide technical assistance to the water user.

October 1990

Chapter 1

Soil-Plant-Water Relationships

Introduction

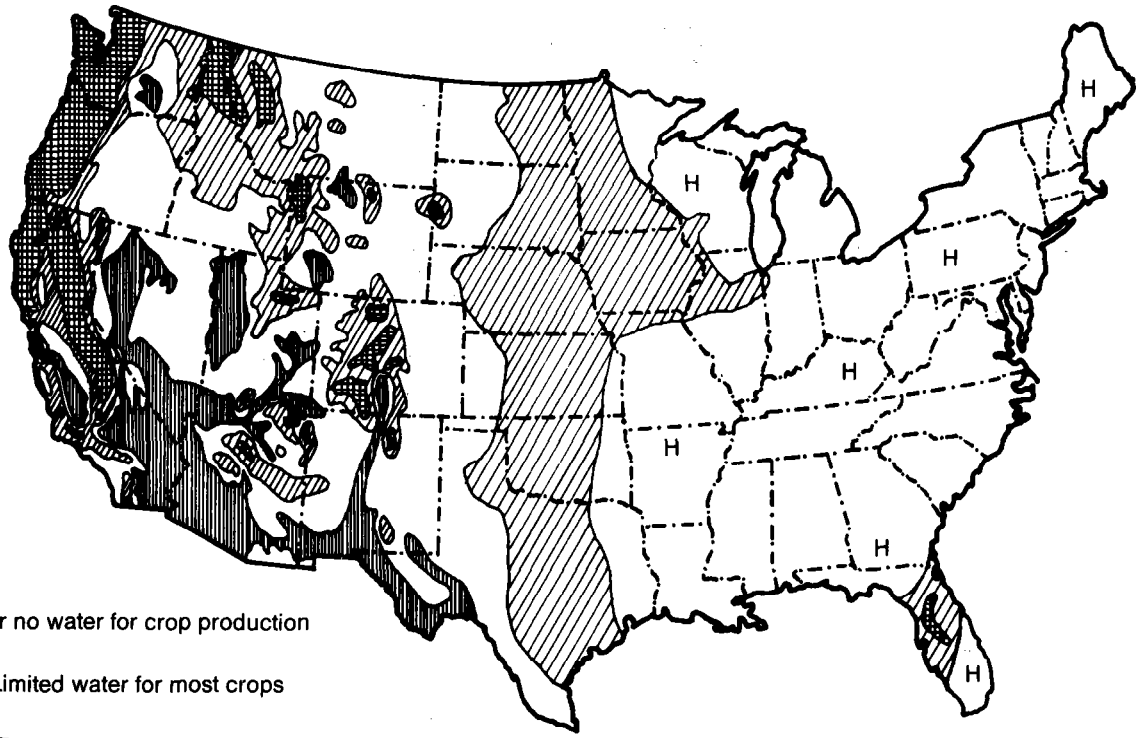
Irrigation is the controlled application of water to arable lands in order to supply crops with the water requirements not satisfied by natural precipitation. In arid climates (fig. 1-1), adequate food and fibers cannot be produced without irrigation. Because of the potential for low crop yields and risk of crop failure due to variations in rainfall, irrigation in semiarid regions is needed most of the time. Furthermore, irrigation in humid and subhumid regions is desirable as insurance against crop losses. Even though summer rainfall ordinarily is sufficient for crop growth, sometime during the year a drought may occur. Production of a profitable crop is generally the objective of agriculture. Irrigation provides the insurance for a profitable agriculture in semiarid, subhumid, and humid areas; it is a necessity in arid regions.

Water is introduced to the soil by an irrigation system, by a regulated water table, or by precipitation. It is stored in the soil matrix and then extracted by plant roots to meet the plant evapotranspirational (ET) needs. This chapter on soil-plant-water relationships treats the physical properties of soils and plants that affect the movement, retention, and use of water and that must be considered in designing and operating systems for conservation irrigation.

In planning and designing an irrigation system, the technician is concerned primarily with the water-holding capacity of a soil, particularly in the root zone of the plant; with the water-intake rate of the soil; with the root system of the crop to be grown; and with the amount of water that the crop uses. In addition, a working knowledge of all soil-plant-water relationships is necessary in order to plan and manage efficiently the irrigation for particular crops grown on particular soils and in order to adjust the design to various conditions.

Figure 1-1.

Four Climatic Areas in the United States: Arid, Semiarid, Subhumid, and Humid



Climatic Area

- Arid - Little or no water for crop production
- Semi-arid - Limited water for most crops
- Subhumid - Requires special farming practices to conserve moisture
- Humid - Enough annual precipitation for most crops, but unevenly distributed

Soil

Soils function as a storehouse for plant nutrients, as habitat for soil organisms and plant roots, and as a reservoir for water to meet the evapotranspirational demands of plant communities. The amount of water that a soil can hold for plant use is determined by its physical and chemical properties. This amount determines the length of time that a plant can be sustained adequately between irrigations or rainfall events. This amount also determines the frequency of irrigation, the amount to be applied, and the capacity of the irrigation system needed for continuous optimum crop growth.

Soil Physical Properties

Mineral soils are porous mixtures of inorganic particles, decaying organic matter, air, and water. They also contain a variety of living organisms. The parent material of mineral soils consists of loose, unconsolidated fragments of weathered rocks or unconsolidated sediments. Physical and chemical weathering, with the translocation and the accumulation of various substances, give rise to a horizontal layering of the soil mass that is frequently visible in trenches and road cuts. Collectively, these horizons or layers are called the soil profile. The characteristics of the layers of the profile affect root growth and the retention and transmission of water in the soil.

Two important physical properties of soils are texture and structure. Soil texture refers to the relative proportion of variously sized groups of mineral particles in a specific soil or horizon. Soil structure refers to the manner in which soil particles are arranged in groups or aggregates. Together, soil texture and soil structure help to determine the supply of water and air in a soil. The inherent characteristics of a soil may be adversely affected by soil compaction. Compaction can extensively modify soil aeration, water retention, transmission properties, root penetration, temperature relations, and the nutritional properties of a soil system.

Soil Texture

Mineral Soil

The variously sized groups of mineral particles in a soil are called separates. The classification of soil separates used by the U.S. Department of Agriculture and their range in diameter size are shown in table 1-1. Coarse fragments, larger than 2 millimeters in diameter, are not included.

Table 1-1.—*Range in particle size by texture*

Soil separate	Particle diameter (millimeters)*
Very coarse sand	2.0 - 1.0
Coarse sand	1.0 - .5
Medium sand	.5 - .25
Fine sand	.25 - .1
Very fine sand	.1 - .05
Silt	.05 - .002
Clay Less than .002	

*millimeters x 0.03937 = inches

Soil textural classes are based on different combinations of sand, silt, and clay. For some purposes it is necessary to make fine distinctions in texture; the basic classes used in terms of size distribution, as determined by mechanical analysis in the laboratory, are shown in figure 1-2.

In places, it is more convenient to speak of texture in general terms; acceptable terms for groups of the basic classes are shown in table 1-2.

In the field, soil texture can be determined by feeling the soil with the fingers. If necessary, this determination can be checked later in the laboratory. The USDA Soil Survey Manual includes the following general definitions of soil textural classes in terms of field experience:

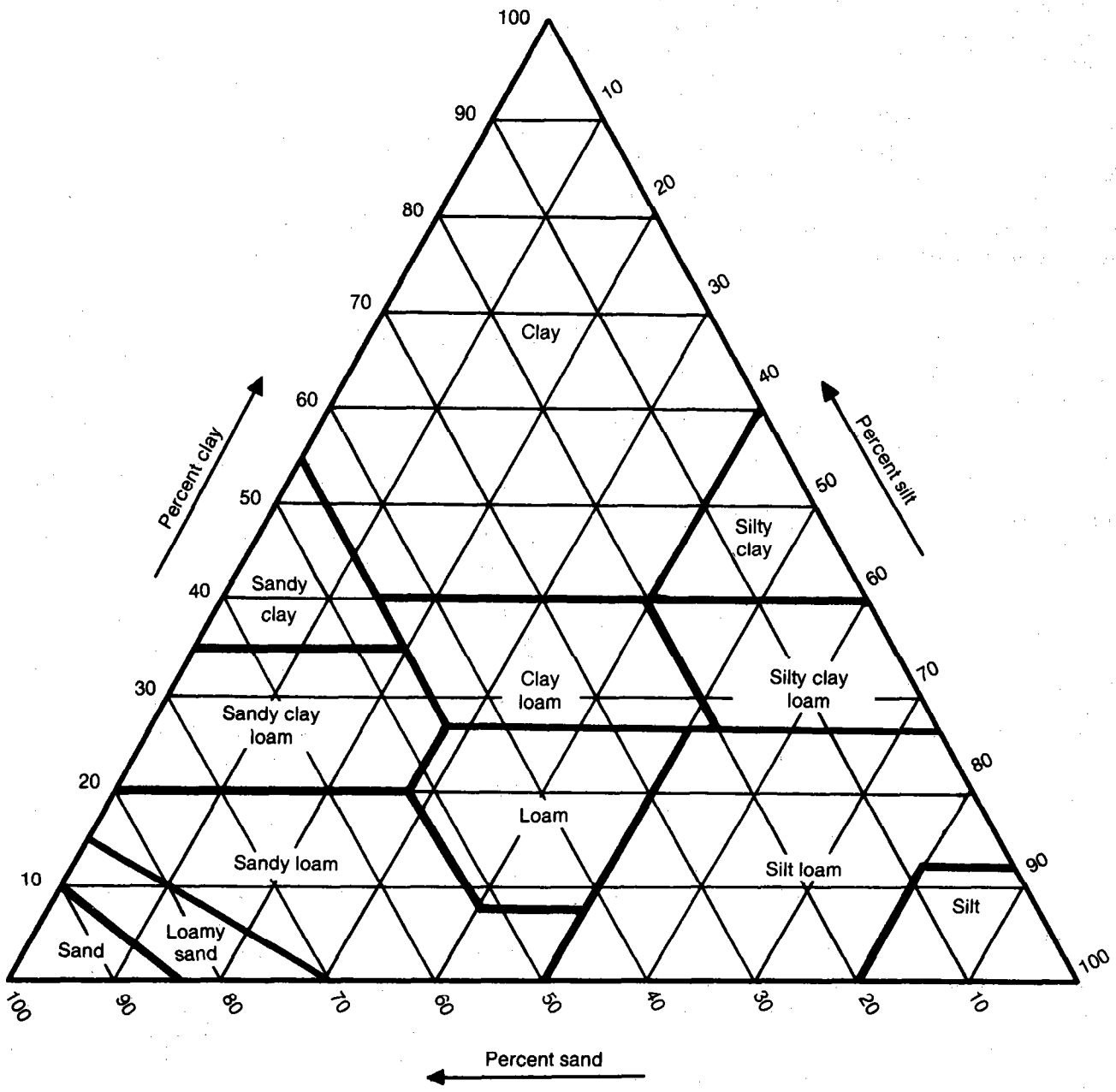
Sand.—Sand is loose and single-grained. The individual grains can be seen or felt readily. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast but crumbles when touched.

Sandy Loam.—A sandy loam is soil containing a high percentage of sand but having enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. Squeezed when dry, a sandy loam forms a cast that falls apart readily. If squeezed when moist, a cast can be formed that bears careful handling without breaking.

Loam.—A loam is soil having a relatively even mixture of different grades of sand, silt, and clay. It is mellow with a somewhat gritty feel but is fairly smooth and slightly plastic. Squeezed when dry, it forms a cast that bears careful handling, and the cast formed by squeezing the moist soil can be handled freely without breaking.

Figure 1-2.

Proportions of Sand, Silt, and Clay in Basic Soil Textural Classes



Silt Loam.—A silt loam is soil having a moderate amount of fine sand and only a small amount of clay; over half of the particles are of the size called silt. When dry, a silt loam appears cloddy, but the lumps can be broken readily; when pulverized, it feels soft and floury. When wet, the soil runs together readily and puddles. Either dry or moist, silt loam forms a cast that can be handled freely without breaking; when moistened and squeezed between thumb and finger, it does not ribbon but has a broken appearance.

Clay Loam.—A clay loam is a moderately fine-textured soil that usually breaks into clods or lumps that are hard when

dry. When the moist soil is pinched between the thumb and finger, it forms a thin ribbon that breaks readily, barely sustaining its own weight. The moist soil is plastic and forms a cast that bears much handling. When kneaded in the hand, clay loam does not crumble readily but works into a heavy compact mass.

Clay.—A clay is fine-textured soil that usually forms very hard lumps or clods when dry and is very plastic and usually sticky when wet. When the moist soil is pinched out between the thumb and finger, it forms a long flexible ribbon. Some clays that are very high in colloids are friable and lack plasticity at all conditions of moisture.

Organic Soil

Organic soils vary in organic matter content from 20 percent to as high as 95 percent. They generally are classified on the basis of degree of decomposition of the organic deposits. The terms peat, muck, and mucky peat are used for organic materials in a manner similar to the way in which mineral textural terms are used. Muck is well-decomposed organic soil material. Peat is raw undecomposed organic materials in which the original fibers constitute almost all of the material. Mucky peat material is intermediate between muck and peat.

Mucky is used to modify mineral soil texture. The term implies the presence of enough organic matter to give the material some properties of organic soil combined with the properties of the mineral material. The material does not, however, have enough organic matter to be "muck." Mucky material is usually dark, friable, and retentive of moisture; it is mineral in basic composition. The organic matter content is commonly more than 10 percent.

Table 1-2.—*General terms for basic soil textural classes (U.S. Dept. of Agr. Soil Survey Manual, 430-V, June 9, 1981).*

General terms	Textural Classes
Sandy soils:	
Coarse-textured	Sands (coarse sand, sand, fine sand, very fine sand), loamy sands (loamy coarse sand, loamy sand, loamy fine sand, loamy very fine sand)
Loamy soils:	
Moderately coarse-textured	Coarse sandy loam, sandy loam, fine sandy loam
Medium-textured	Very fine sandy loam, silt loam, silt
Moderately fine-textured	Clay loam, sandy clay loam, silty clay loam
Clayey soils:	
Fine-textured	Sandy clay, silty clay, clay

Soil Structure

Soil structure is the arrangement and organization of soil particles into natural units of aggregation that soil scientists call peds. Peds are separated from one another by planes of weakness that persist through cycles of wetting and drying in place. Most peds are large enough to be seen without magnification. Structure influences the rate at which water and air enter and move through the soil; it also affects root penetration and the nutrient supply of the soil.

Structure type (fig. 1-3) refers to the particular kind of particle grouping that predominates in a soil horizon. Single-grained and massive soils are structureless. In single-grained soils, such as loose sand, water percolates very rapidly. Water moves very slowly through massive soils such as some clays. The more favorable water relations are usually in soils that have prismatic, blocky, and granular structure; platy structure impedes the downward movement of water.

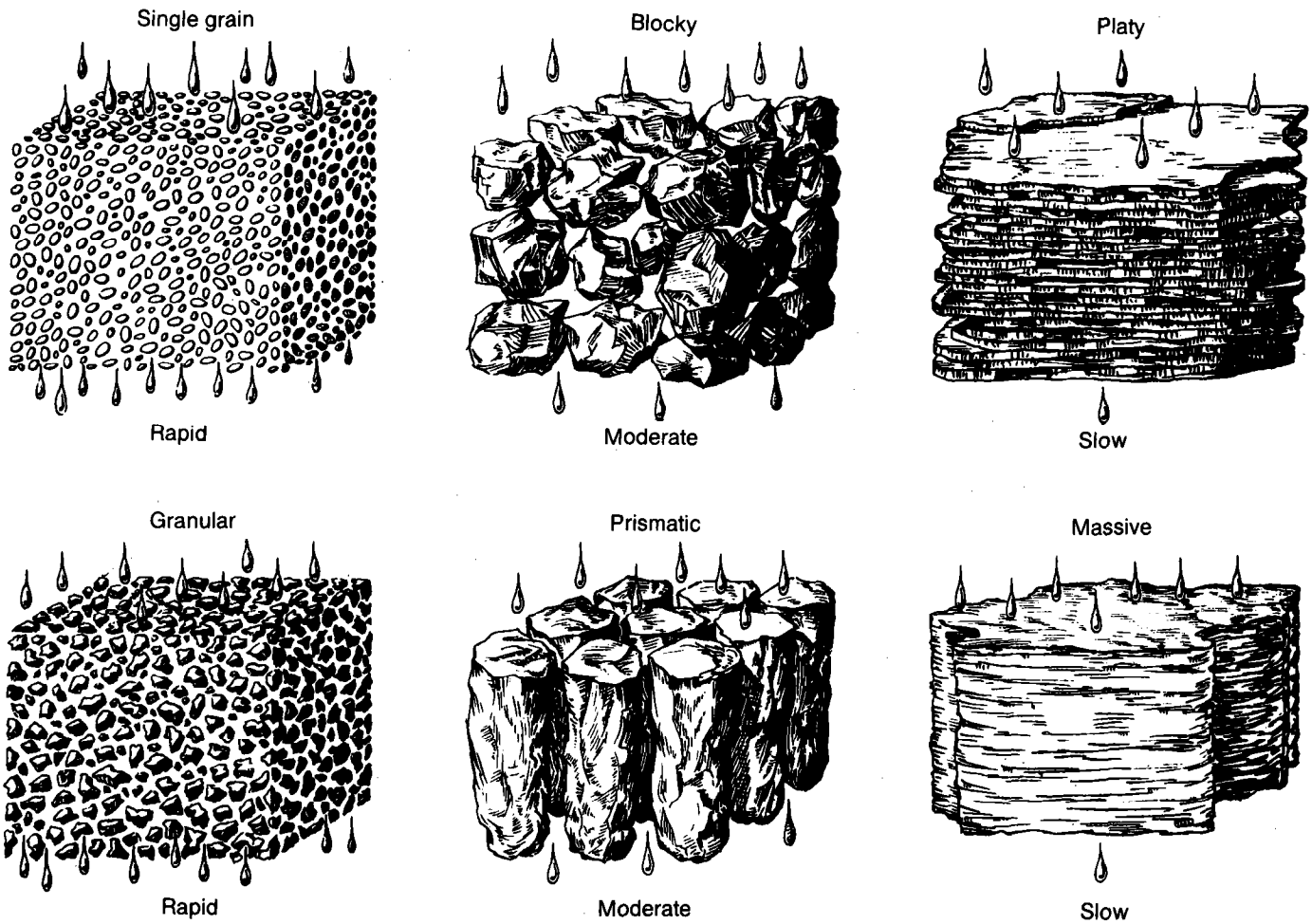
Unlike texture, structure of the soil can be changed to the depth of tillage. Excellent structure develops in the surface layer of soils high in organic matter and on which perennial grass is growing. Cycles of wetting and drying or of freezing and thawing improve structure in the plow layer. On the other hand, cultivation of medium- or fine-textured soils when their moisture content is high tends to destroy structure. Irrigation water that contains large amounts of sodium causes very undesirable structure by dispersing the soil aggregates.

Tilth

The physical condition of the soil in relation to plant growth and ease of tillage is commonly referred to as tilth. It depends on both the degree and stability of soil aggregates. Good, fair, and poor are the common descriptive terms for tilth. They refer to the ease with which a soil can be tilled

Figure 1-3.

Types of Soil Structure and Their Effect on Downward Movement of Water



and the rate it takes in water. Good soil tilth can be achieved on most soils by using good soil management practices.

Soil Porosity

The volume of pore space in mineral soils generally ranges from 30 to 60 percent of the total volume with the average being close to one-half. Soil porosity is affected mostly by soil aggregation, texture, root activity, entrapped gases, and by burrowing insects, worms, and other animals. Coarse-textured soils tend to be less porous than fine-textured soils, but the mean size of individual pores is usually larger in sandy soils. Porosity tends to be more variable in clayey soils because of the potential for swelling and contracting during wetting-drying cycles and the greater ability to either aggregate or disperse.

Pore space in soils can be viewed as a vast interconnecting network of voids extending in all directions. The voids hold liquids and gases and regulate their movement, contain most of the living organisms, and serve as avenues of entry for roots to grow and expand. Total soil porosity can be determined for a soil sample from the equation:

Total porosity = 1 - (bulk density/average particle density)

Bulk density is generally measured by means of a core sampler, of known volume, designed to extract undisturbed samples from various depths in the profile. Using the water displacement technique, soil scientists sometimes determine bulk density from a clod sample. Pore-size distribution can

be measured in the laboratory by desorption methods in which a presaturated sample is subjected to a stepwise series of incremental suctions, and the capillary theory is used to obtain the equivalent pore-size distribution. Where aggregation is quite distinct, it is possible to divide pore-size distribution into macropores and micropores. The macropores are primarily the pore spaces between aggregates that serve as the principal avenues for water infiltration, drainage, and aeration. The micropores are the smaller pores inside aggregates that function mostly for the retention of water and solutes. The demarcation is seldom distinct, and the separation between macropores and micropores is largely arbitrary.

Soil Compaction

Compaction of agricultural soils generally refers to the reduction of soil porosity through the partial collapse of the pores and expulsion of the permeating air. In an agricultural sense, soils are considered to be compact when the air-filled porosity is low enough to restrict aeration which impedes root penetration and drainage.

Soils may become compact naturally as a result of their textural composition, moisture regime, or the manner in which they are formed. Frequently, agricultural soils become compact as a result of mechanical force applied to the soil surface during cultural operations. Trampling by livestock can cause soil compaction; however, the most common cause of soil compaction in contemporary agriculture is that imposed on the soil by wheels, tracks, and soil-engaging tools. Figure 1-4 illustrates the effect of increased compaction (high-bulk density) on the growth and proliferation of alfalfa roots at the end of 80 and 110 days in greenhouse pots. Longer growth periods did not change root length density much beyond that shown for the 110-day period.

Soils of the southeast United States characteristically do not allow crops to develop a deep root system. Many of these soils have a textural class, such as the sandy loams, that is receptive to soil compaction by traffic and excess tillage in seed-bed preparation. Such soils may become increasingly restrictive to rooting.

Soil Salinity and Sodicity

Saline and sodic soils are most common in arid and semiarid regions, because rainfall is inadequate to meet the potential evapotranspiration requirement of plants. These soils occur when salts are not leached and accumulate to levels detrimental to plant growth. Salt problems can develop in subhumid and humid regions, particularly near coastal regions. It is estimated that 5 million hectares of irrigated land in the United States are salt affected, mostly in the 17 Western States. As much as one-third of all irrigated lands in the world (about 70 million hectares) have salt problems.

There are three main natural sources of soil salinity, namely: mineral weathering, atmospheric precipitation, and fossil salts. In addition, salts are added to soils by irrigation and agricultural and industrial wastes. Salts commonly are transported from areas of overirrigation to accumulate in poorly drained areas. As drainage water or irrigation return-flows evaporate, high concentrations of salts remain.

Normal irrigation involves applying water to the soil surface and displacing unused water through the soil during subsequent irrigations. Some drainage water also may pass eventually below the crop root zone. Water is lost through evaporation at the soil surface and through transpiration. Both evaporation and transpiration increase the residual concentration of dissolved salts. Salt concentration normally increases with soil depth in well-drained soil. As the proportion of irrigation water passing through the root zone (the leaching fraction) is increased, salt accumulation in the lower profile decreases.

When soils are irrigated with waters containing large amounts of sodium, the exchangeable sodium levels may become quite high. Such soils frequently crust severely and swell or disperse, which greatly decreases the hydraulic conductivity or permeability of the soils to water.

Categories of Salt-Affected Soils

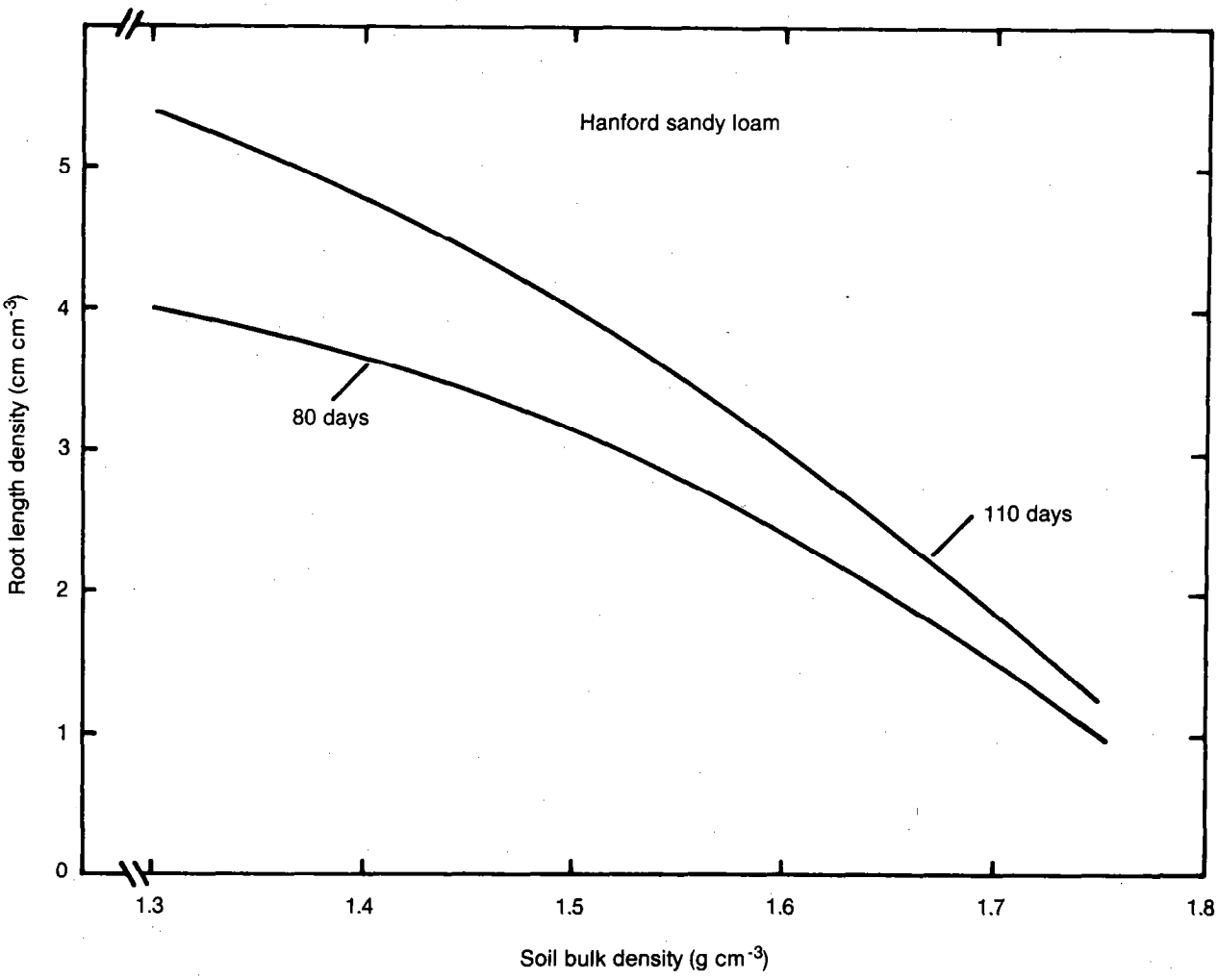
The classification of salt-affected soils is based on the soluble salt concentrations in extracted soil solutions. Electrical conductivity (EC_e) of a saturated extract is the standard measure of salinity. Table 1-3 gives the salinity class associated with electrical conductivity of soil saturation extracts that are in use by the Soil Conservation Service.

The sodium adsorption ratio (SAR) is the standard measure of the sodicity of a soil; it replaces the previously used exchangeable sodium percentage. The sodium adsorption ratio is calculated from the concentrations (in milliequivalents per liter) of sodium, calcium, and magnesium ions in the saturation extract according to the following relationship:

$$SAR = Na/ [(Ca + Mg)/2]^{1/2}$$

Figure 1-4.

Effect of Soil Bulk Density on Alfalfa Root Growth in Greenhouse Pots at the End of 80 and 110 Days



Soil Water

Soil water is frequently described in terms of content in units of gravimetric percent, percent on a volume basis, or equivalent water depth per unit of soil depth. Such descriptions are usually adequate for irrigation considerations when the primary question is one relating to how much irrigation water is required to bring the soil back to a defined water content. A descriptive property is needed, however, to explain why soils treated in similar ways have different water contents; why plants respond differently on contrasting soils even though they have the same water content; and why if a sandy soil and clay soil have the same water content and are placed in intimate contact with one another, water will move from the sandy soil to the finer textured soil. Soil water potential is the property used to describe such a phenomenon.

Soil Water Potential

Total water potential is the amount of work required per unit quantity of pure water to transport, reversibly and isothermally, a small quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration. Differences in potential energy of water from one point in a soil system to another give rise to the tendency of water to flow within the soil. In the soil, water moves continuously in the direction of decreasing potential energy.

Table 1-3.—*Classification of salt-affected soils.*

Class	Electrical conductivity (EC_e)* Siemens per meter (S/M)	Decisiemens per meter (dS/m)**
Very slightly saline	0 - 0.4	0 - 4
Slightly saline	0.4 - 0.8	4 - 8
Moderately saline	0.8 - 1.6	8 - 16
Strongly saline	>1.6	>16

*Corrected to a temperature of 25 degrees C.
**Decisiemens per meter = millimhos per centimeter.

The concept of soil-water potential is of great fundamental importance. It replaces the arbitrary categorizations (gravitational water, capillary water, hygroscopic water) that were used in the early development stages of soil physics. Water in the soil differs from place to place and from time to time, not in form, but in potential energy. For very practical reasons, however, it is convenient to retain the concepts of "field capacity" and "permanent wilting point," while recognizing the qualitative aspects of such nomenclature.

Total water potential consists of several conponents. It is the sum of matric, solute, gravitational, and pressure potential:

Total = Matric + Solute + Gravitational + Pressure

Units of the potential depend on how a unit quantity of water is specified. Because weight is one of the most convenient ways of specifying the unit of water and conversions between English and SI (International System) are easily done, this will be used in some illustrations.

Gravitational Potential.—Determination of gravitational potential is illustrated in figure 1-5. This component of total potential is independent of soil properties and depends only on the vertical distance between the reference and the point in question. For points above the reference, gravitational potential is positive; points below the reference are negative. In figure 1-5 two points in a soil are located at a specific distance from a reference point Z. Gravitational potential of point A is 6 inches and of point B is 4 inches, thus the difference in gravitational potential between the two points is 6 inches - (-4 inches) = 10 inches.

Matric Potential.—When the unit quantity of water is expressed as weight, then matric potential is the vertical distance between the measured point of the soil (ceramic cup of figure 1-5) and the water surface of a water-filled manometer. Matric potential is a dynamic soil property and will be at a theoretical zero level for a saturated soil. The matric potential of a soil system results from capillary and adsorptive forces due to the soil matrix. These forces attract and bind water in the soil and lower its potential energy below that of bulk water. Capillarity results from the surface tension of water and its contact angle with the solid soil particles. This potential was formerly called capillary potential or capillary water. In figure 1-5 the unglazed ceramic cup that is embedded in soil is connected to a water manometer to form a tensiometer. The weight matric potential of the soil water at the cup is the vertical distance from the center of the cup to the water level in the manometer which is 6 inches.

Pressure Potential.—The pressure potential applies mostly to saturated soils. Where water quantity is expressed as a weight, pressure potential is the vertical distance between the water surface and a specified point. In the field, this component is zero above and at the level of water in the piezometer. Below the water level it is always positive. In figure 1-5 a piezometer tube (tube open at both ends) is installed in the soil to a depth below the water table. Pressure potential at point A is the distance between the point and the water level which is 4 inches.

Solute Potential.—Solute or osmotic potential arises because of soluble materials (generally salts) in the soil solution and the presence of a semipermeable membrane. Two recognized membranes in soil-water systems are the cell wall of plant roots and air-water interfaces. The solute potential can be approximated from the relation:

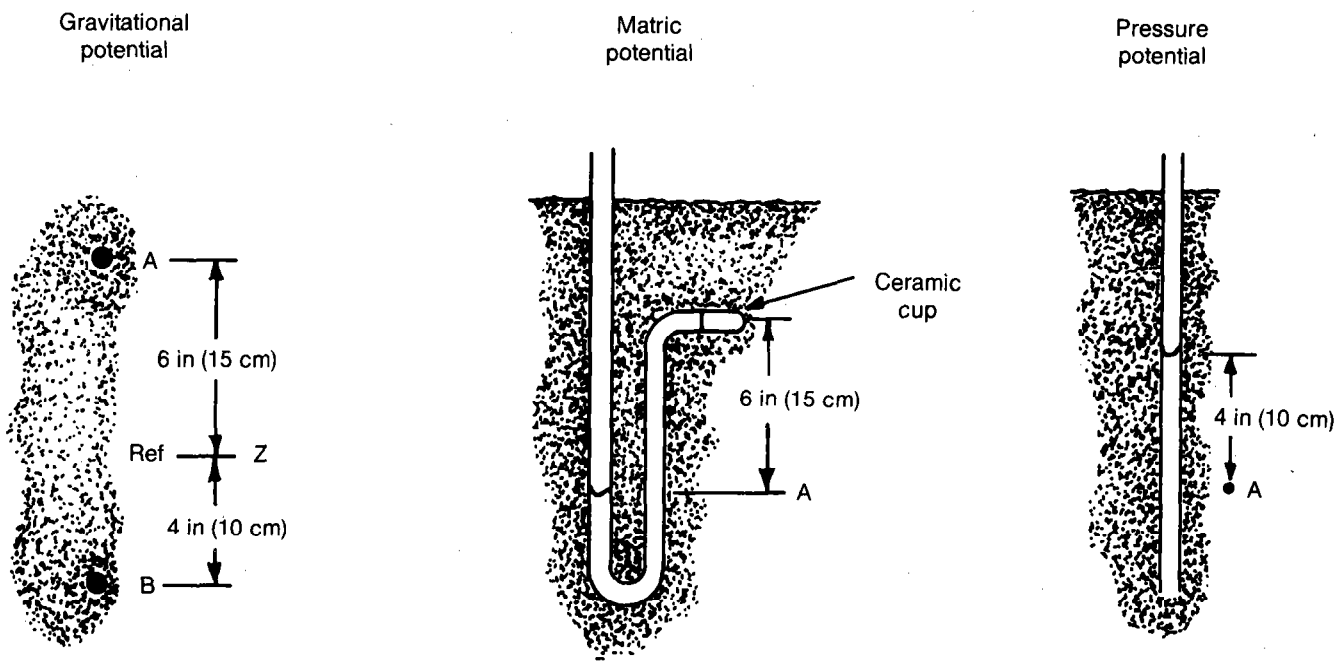
$$\text{Solute potential} = RTC$$

where R is the universal gas constant (82 bars cm^3/mol °k), T is absolute temperature (°k), and C is solute concentration (mol/cm^3). Because of the nature of the universal gas constant (R), it is much easier to use SI units in solving for solute potential. With the units illustrated, as values of temperature and solute concentration are placed in the equation, all units cancel except bars. This unit (bar) is now easily converted to another unit as shown in the following discussion.

Units.—Historically, many units have been used to express suction, tension, stress, or potential. A partial list is: bars, centimeters (cm) of water, centimeters of mercury, inches of water, atmospheres, centibars, millibars, joules per kilogram,

Figure 1-5.

Illustrations and Example Calculations for Gravitational, Matric, and Pressure Potential Based on Weight as Specifying the Unit of Water. Increasing Depth Below the Soil Surface is Considered to be Negative in the Illustrations.



pounds per square inch, ergs per gram, and dynes per square centimeter. The bar unit is in extensive use; some conversions for this unit are:

1 bar = 1020 cm of water
= 75.01 cm of mercury
= 401.5 inches of water
= 0.987 atmospheres
= 100 centibars
= 1000 millibars
= 100 joules/kg
= 10^6 ergs/g
= 10^6 dynes/cm^2

Soil Water Characteristic Curves

When saturated soils are subjected to increasing amounts of suction, progressively smaller pores are drained until, at very high suctions, only the very narrow pores retain water. Also, an increase in soil-water suction is associated with a decreased thickness of the water film that covers the surface of soil particles. The amount of water remaining in the soil at a series of equilibrium steps is related to the size and volume of water-filled pores and is, therefore, a function of the matric suction. Experimentally, pressure is substituted for suction with appropriate equipment and a curve of water content versus soil moisture tension is prepared. Illustrative curves for contrasting soil types are shown in figure 1-6. The relation between matric potential changes and changes in water content is a complex, nonlinear function. This characteristic curve is usually determined for individual soils.

Water Movement in Soil

Under saturated conditions, the rate of water movement in a soil system is governed by the characteristics of the pore space; therefore, the actual geometry and flow pattern of a soil is extremely complex. An equation known as Darcy's law is used to express the flux density (volume of water flowing through a unit cross-sectional area per unit of time). The equation is:

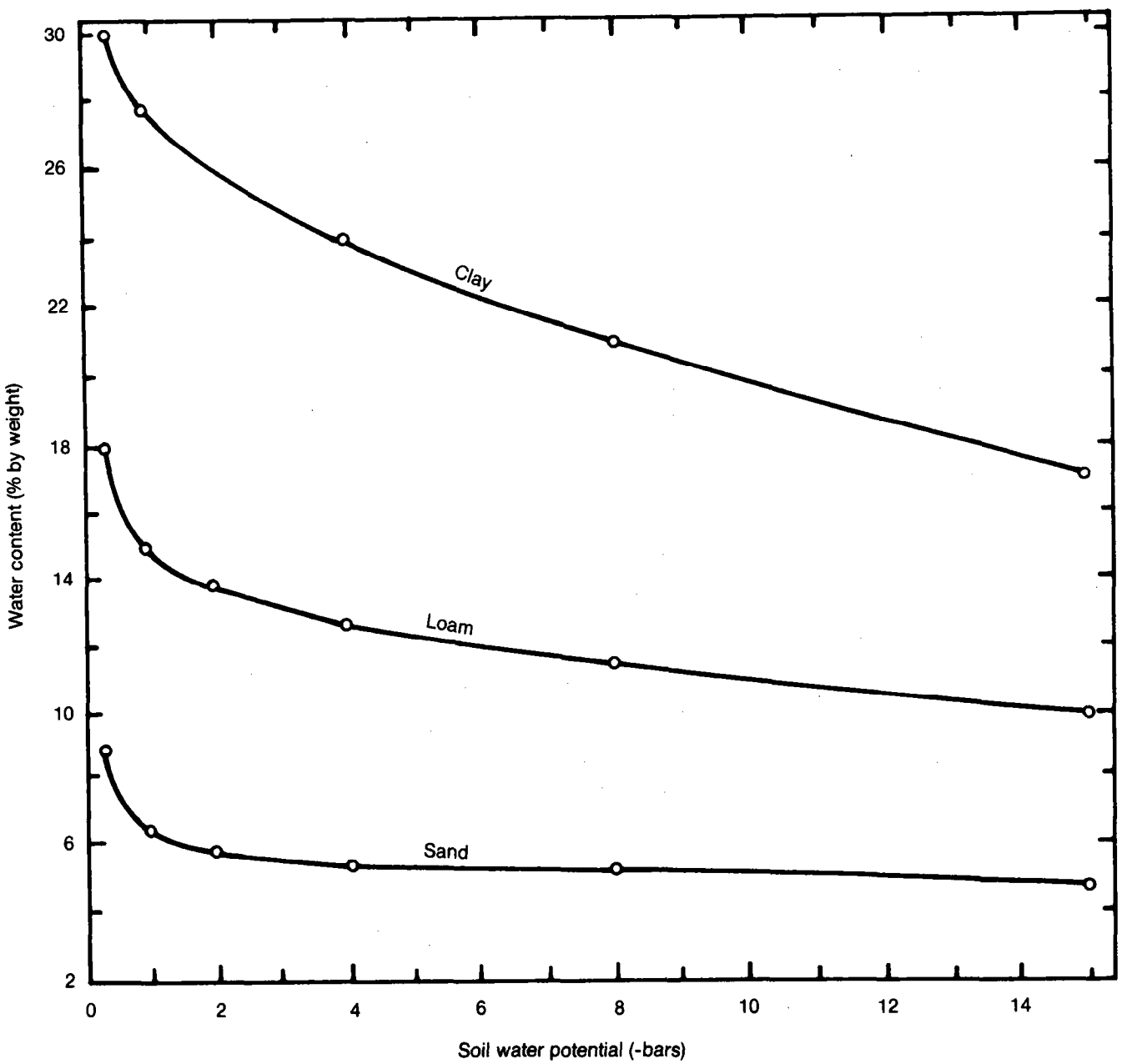
$$q = K \text{ (delta H)}/L$$

where q is the flux density, (delta H)/L is the hydraulic gradient (head drop or change in head per unit distance in the direction of flow), and K is the proportionality factor generally designated as the hydraulic conductivity. The K factor reflects the complexities of individual soil systems. This law indicates that the flow of water through the soil is in the direction of, and at a rate proportional to, the driving force acting on the system.

Many processes involving water movement or flow in the crop root zone occur under unsaturated conditions. In

Figure 1-6.

Soil Water Characteristic Curves



comparison to saturated flow, water movement under unsaturated conditions is considerably more complex and difficult to describe quantitatively; however, many excellent quantitative reviews on this subject are available for definitive information. An overview of practical unsaturated flow characteristics will be considered here.

Under unsaturated conditions water in soils is subject to subatmospheric pressure that is equivalent to a negative pressure potential. A gradient of this potential constitutes a driving force. Matric suction, as pointed out earlier, is due to the affinity of water to the soil-particle surfaces and capillary pores. Water is drawn from a region where hydration films are thicker to where they are thinner and from a zone where capillary menisci are less curved to where they are more highly curved. In other words, water flows from a region of higher to a region of lower matric potential (low to high suctions).

For saturated flow, the hydraulic conductivity (K) of a given soil will remain constant. Under unsaturated conditions, K changes drastically with water content. Large, more highly conductive pores are drained first; therefore, K decreases dramatically as a given soil dries. Because different soils have varying pore space characteristics, K values also are markedly different; contrasting textural soil classes influence unsaturated hydraulic conductivity in a very pronounced way. Generally, a saturated sandy soil will conduct water more rapidly than a saturated clay soil. As the soils drain, the very opposite conditions prevail; the small pores of the clay soil will retain and conduct water even at appreciably low potentials. Under unsaturated field conditions, flow is much more pronounced with fine-textured soils than with sandy soils.

From this discussion it is evident that water moves in soils in any direction in relation to potential energy gradients. The rate and magnitude of movement is determined by the many and complex relations that exist in soil systems. Some practical implications of textural class are illustrated in figure 1-7.

Plant Available Water

In designing an irrigation system, information is needed on how much of the water in soils is available to plants; the soil functions as a reservoir that has a limited capacity. Traditionally, plant available water has been considered to be the amount of water held by the soil between field capacity (FC) and permanent wilting point (PWP). These two points provide only qualitative information on soil water retention properties; nevertheless, their usage continues and useful planning information can be obtained from these concepts. It is important, however, to understand the limitations that are imposed.

By definition, FC is the amount of water a well-drained soil holds after "free" water has drained off. For coarse-textured soils drainoff occurs soon after irrigation because of their relatively large pores. In fine-textured soils drainage takes much longer because of their small pore size. Soil properties that affect field capacity materially are texture and strata within the profile that restrict water movement. Fine-textured soils hold more water than coarse-textured soils. Field capacity for sandy soils is defined as –1/10 bar, for silty soils, –1/5 bar; and for clayey soils, –1/3 bar. Restricted flow in stratified soils slows redistribution, but may increase the amount of water used by the plant. The effect of contrasting soil texture on the soil-water potential is illustrated in figure 1-8 by the broken line near the left vertical axis. Field capacity can be determined in the field after a soil has been thoroughly wetted by irrigation or rain or estimated in the laboratory from water-characteristic relations.

The permanent wilting point (PWP) is the soil-water content at which plants can no longer obtain enough water to meet minimal transpiration requirements; at which time, they wilt and if watered will not recover. Plants will wilt if they are not able to take up soil water fast enough to meet the climatic ET demand.

Plants continue to absorb water when wilted, but not at a sufficient rate to regain turgor.

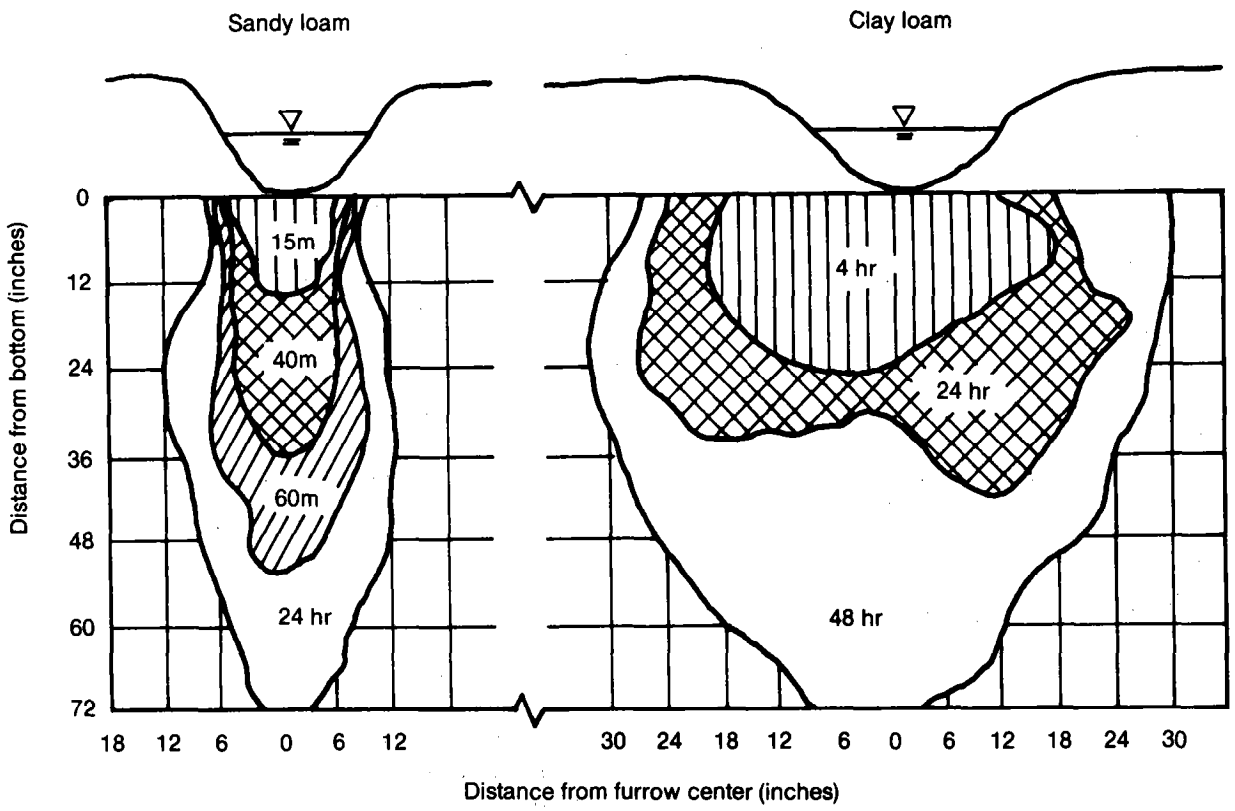
The water potential commonly used for PWP is -15 bars, which was first established with sunflowers over a wide range of soils. This parameter is shown as the right vertical line of figure 1-8. Some plants can extract soil water to potentials below -15 bars before they wilt and some will wilt above -15 bars.

Soil water considered to be available for plant growth lies at a potential energy level between FC and PWP. It should be pointed out, however, that these determined values represent only the matric potential of the soil water system. The presence of salts may contribute a substantial osmotic component to the total soil water potential. It is the total potential that determines soil water availability to plants. Nevertheless, it is helpful to examine some effects of soil texture on the water held between FC and PWP. For soils low in soluble salts, the finer the texture the greater the available water capacity (AWC).

Figure 1-9 shows the variation in FC and PWP water content by texture. Soil water content in percent by dry weight of soil is shown on the left margin and soil water content in inches of water per foot of soil is shown on the right margin for various soil bulk densities. The figure may be used as a general guide for estimating the AWC of soils based on texture until local curves can be developed. It applies generally to uniform soil profiles with low salt content.

Figure 1-7.

Water Penetration and Movement in Sandy and Clay Loam Soils; to Achieve Complete Wetting, Furrows Have to be Closer Together on Sandy Soils.



Generally, well-drained sandy soils have a low available water capacity. Silty soils have a good available water holding capacity, as do clay loams and clays. Table 1-4 provides a general guide of available water ranges for given soil textural classes.

While FC is considered to be the upper limit of available water, it should be pointed out that this is not strictly true. Water moving downward in the soil following an irrigation or rainfall can be effectively used by growing plants. Because this is a transitory stage, this water is generally not considered in calculations to determine the available water retaining capability of a soil but may affect irrigation scheduling.

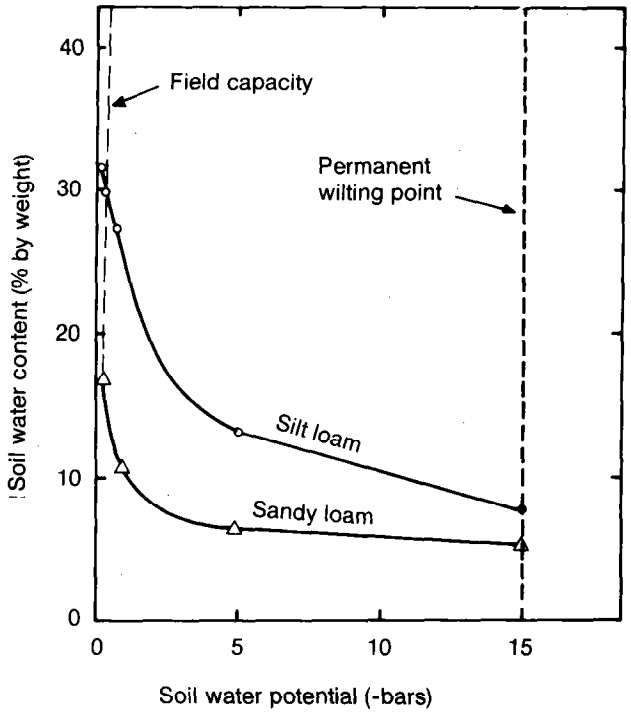
Water held between FC and PWP is frequently considered to represent 100 percent of the available water supply. The water release characteristic curve of figure 1-6 is replotted in figure 1-10 to illustrate this concept. From figure 1-10 it is clear that a given level of allowable depletion, for example,

Table 1-4.—*Ranges in available water content by soil textural classes.*

Textural class	Inches of water per inch of soil depth or cm of water per cm of soil depth		
Very coarse sand	0.03	-	0.06
Coarse sand—loamy sand	0.06	-	0.10
Sandy loam—fine sandy loam	0.10	-	0.14
Very fine sandy loam—silt loam	0.12	-	0.19
Sandy clay loam—clay loam	0.14	-	0.21
Sandy clay—clay	0.13	-	0.21
Peat and muck	0.17	-	0.25

Figure 1-8.

Relation Between the Water Content and the Water Tension of a Soil



the 50 percent level, will represent very different soil water potentials when water has been used by plants to that extent. This point is discussed further in the irrigation scheduling section. Calculations relating to plant available water are presented under water balance.

The dynamic nature of how plant roots extract soil water is shown in figure 1-11. Cotton was planted on April 16 in the San Joaquin Valley, California, and the soil water content of the profile at that time can be taken to represent FC. No rainfall occurred during the growing season, and the crop was not irrigated. By harvest, some soil water was extracted at total water potential lower than PWP at depths shallower than 160 centimeters. Limited root growth in the lower parts of the profile, however, resulted in some water that was held at greater than -15 bars being unused by harvest time.

Soil Water Measurement

The measurement of water stored in soils and the capacity of soils to store water are important. That some soils in the humid climates produce crops despite the lapse of many days, and sometimes weeks, between periods of rainfall is evidence of their capacity to store available water, because all growing plants require water daily. In irrigated regions, the depth of water to apply in each irrigation and the interval between irrigations are both influenced by storage capacity of the soil; therefore, the capacity of soils to store available water for use by growing crops is of special importance and interest. Irrigated soils that have large water-storage capacity may produce profitable crops in places where there is a shortage of irrigation water.

Knowledge of the capacity of soils to retain available irrigation water is essential for efficient irrigation. If the irrigator applies more water than the root-zone soil reservoir can retain at a single irrigation, the excess is wasted. If less is applied than the soil will retain, the plants may wilt from lack of water before the next irrigation unless water is applied more frequently. Irrigations are scheduled in humid areas in order to make efficient use of rain. Water losses which result from deep percolation below the root zone of crops cannot be seen. Losses can be determined or approximated by subtracting the storage capacity of the various soils from the amount of water applied in single irrigations, less the runoff.

Methods Used for Characterizing Soil Water

The best and most effective way of determining when to irrigate is to measure or to estimate the water level in the soil. By knowing the amount of water that is available, the irrigator who has knowledge of and experience with a particular crop on a particular soil can accurately determine

Figure 1-9.

General Relationship Between Soil Water Characteristics and Texture

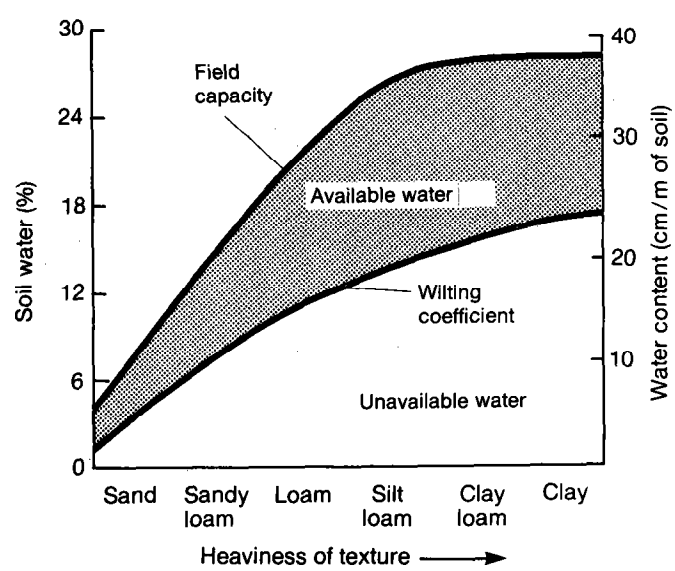
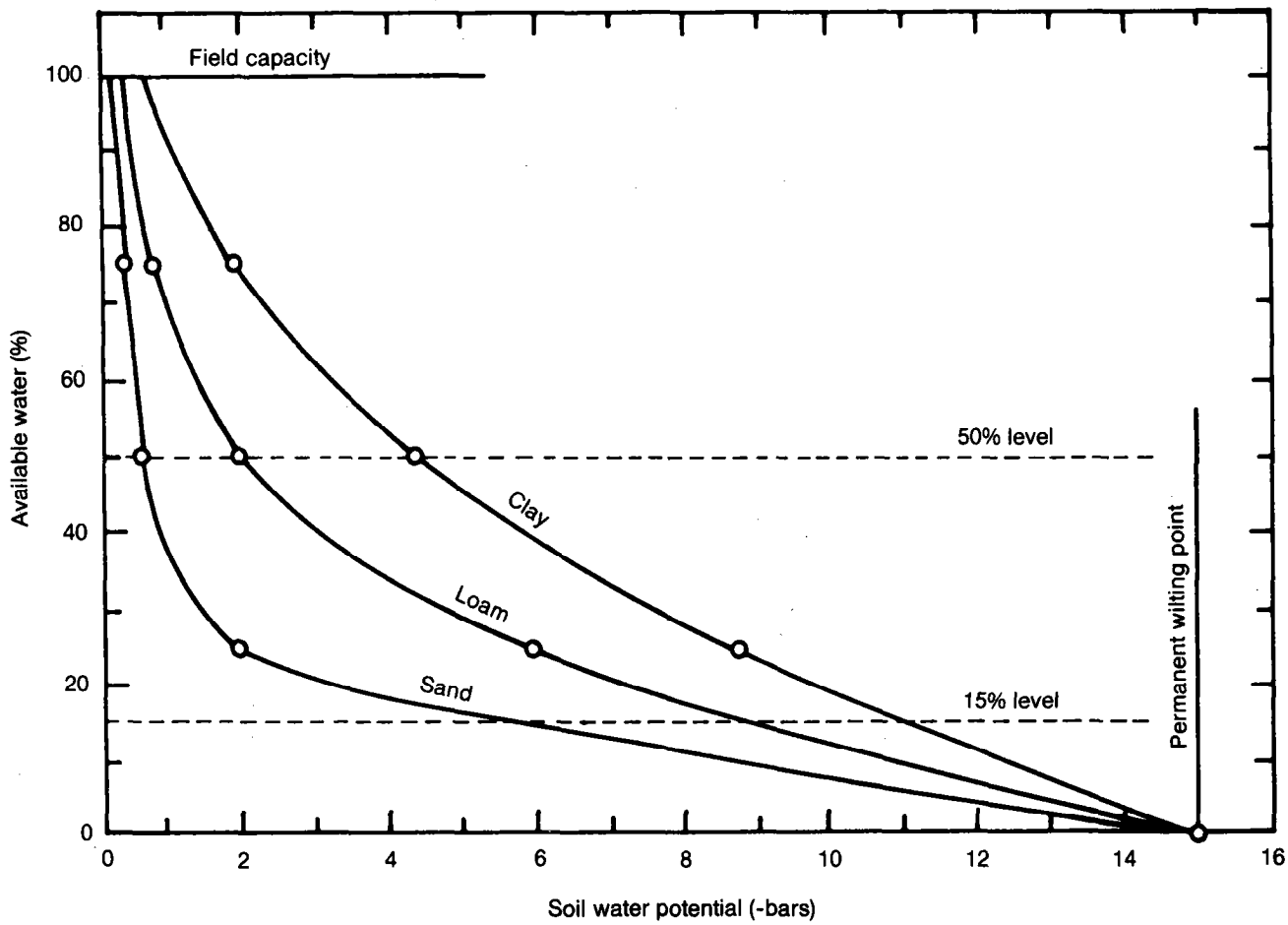


Figure 1-10.

Water Release Curve for Three Soils



when irrigation is needed. Of the numerous methods that can be used to measure and estimate soil water, many are not suited to field use. But several methods are now being used by irrigators and others are being developed that show promise as methods of determining when to irrigate. Some of these methods are discussed in the following pages.

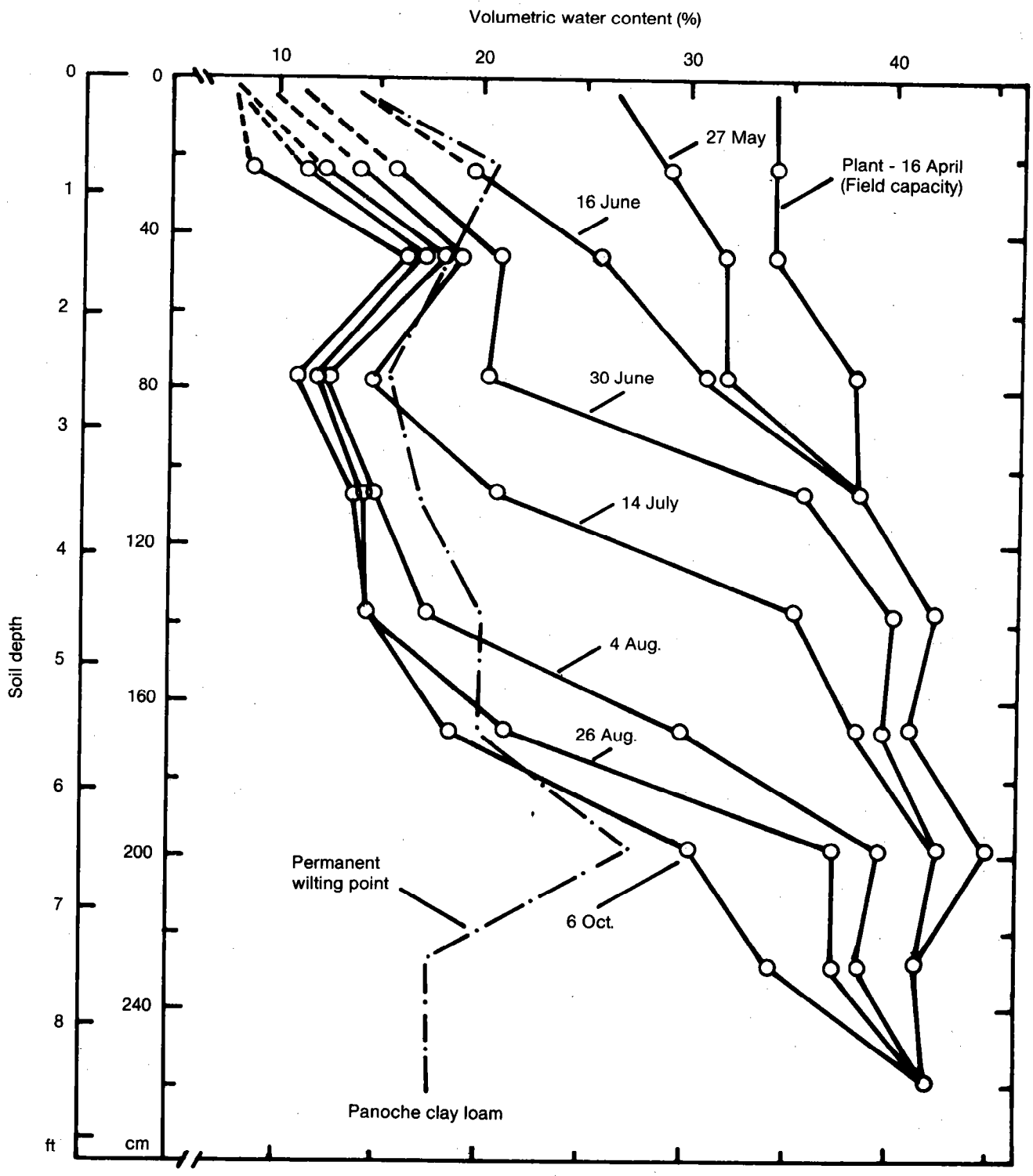
Gravimetric—The gravimetric method is the accepted standard for soil water measurement. Soil samples are taken from a desired depth at several locations in a field for each soil type. Samples are weighed, dried in an oven for 24 hours at 105 to 110 degrees centigrade, and then weighed again. The difference in weight is the amount of water, dry weight basis, in the soil, which can be converted to inches or centimeters of water remaining in the soil.

Although this method gives good results, it is not used generally by growers. Its accuracy depends on the number of samples taken and on the skill used in obtaining and handling the samples. It requires using facilities not ordinarily owned by growers and requires much time and labor. The method is used principally in experimental work and is a standard against which other methods of soil water determination can be compared.

Feel and Appearance Method—How soil samples taken in the field from appropriate locations and depths feel and look gives some indication of water content. A shovel can be used to get samples, but for some soils a soil auger or a sampling tube is better. The reaction of the soil to three field tests are recorded and compared to locally developed feel and water

Figure 1-11.

Soil Water Depletion by Cotton on a Panoche Clay Loam



content. These three tests are as follows: the ball test where the soil is squeezed several times into a firm ball, and then dropped from several heights and the effects are recorded; the rod test where the soil is rolled to form a 0.10-inch (3 mm) diameter rod and then it is held out vertically and the effect on the length is measured and recorded; and the ribbon test where the soil material is smeared out between the thumb and first finger and the length of the resulting ribbon is recorded. Although gauging water conditions by feel and appearance is not the most accurate method, with experience the irrigator should be able to estimate the soil water content level within 10 to 15 percent. This method is inexpensive, but acquiring the soil samples is a lot of work.

Tensiometers—Tensiometers (fig. 1-12) work on the principle that a partial vacuum is created in a closed chamber when water moves out through a porous ceramic cup to the surrounding soil. Tension is measured by a water manometer, a mercury manometer, or a vacuum gauge. The scales are generally calibrated in either hundredths of an atmosphere or in centimeters of water. Tensiometers that utilize a mercury manometer are usually preferred as research tools because they afford great precision. Because of their simplicity, tensiometers equipped with Bourdon vacuum gauges are better suited to practical use and to irrigation control on particular soils.

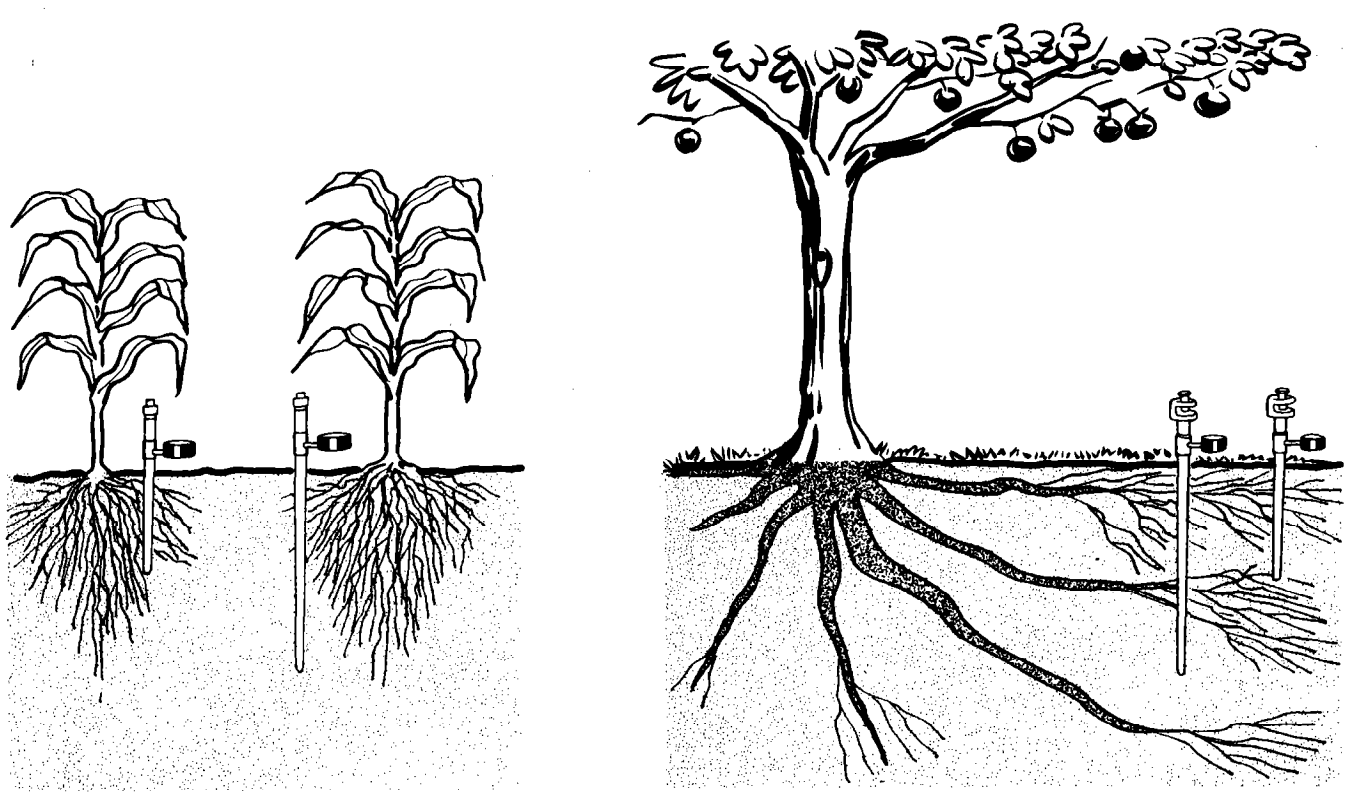
The cup of the tensiometer is placed in the soil at the desired depth, after which the instrument must be filled with water. Water moves through the porous cup until water in the cup and the water in the soil reach equilibrium. Any increase in tension that occurs as the soil dries causes the above ground vacuum-gauge reading to increase. Conversely, an increase in soil-water content reduces tension and lowers the gauge reading. The tensiometer continues to record fluctuations in soil-water content unless the tension exceeds 0.85 atmosphere; at which point, air enters the system and the instrument ceases to function. If this occurs, the instrument must again be filled with water before it can operate after an irrigation or rain.

Some experience is required to use a tensiometer. If air enters the unit through any leaks at the rubber connections, measurements are not reliable. Air leaks can also result from faulty cups as well as at the contact points of the setscrews used to secure the porous cup to the metal support. Some manufacturers provide a test pump that can be used to test the gauge and to remove air from the instrument.

Tensiometer readings reflect soil water tension only; that is, they indicate the relative wetness of the soil surrounding the porous tip. They do not provide direct information on the amount of water held in the soil. Tension measurements are useful in deciding when to irrigate, but they do not indicate how much water should be applied. A special water-characteristic curve for the particular soil site is needed to convert

Figure 1-12

Tensiometers Are Used to Measure Soil Water



water-tension measurements into available water percentages.

Tensiometers do not satisfactorily measure the entire range of available water in all soil types. But they probably are the best field instruments to use to determine water conditions in medium to coarse textured soil in the wet range. They are best suited to use in sandy soils because in these soils a large part of the water available to plants is held at a tension of less than 1 atmosphere. Tensiometers are less well suited to use in fine-textured soils in which only a small part of the available water is held at a tension of less than 1 atmosphere. Tensiometers are usually installed in the lower half of the root zone in finer textured soils in order that the readings are within the gauge range even though appreciable water has been extracted.

Electrical-Resistance Instruments—These instruments use the principle that a change in water content produces a change in some electrical property of the soil or of an instrument in the soil (fig. 1-13). They consist of two electrodes permanently mounted in conductivity units, usually blocks of plaster of Paris, nylon, fiber glass, gypsum, or combinations of these materials. Electrodes in the blocks are attached by wires to a resistance or conductance meter that measures changes in electrical resistance in the blocks. When the units are buried in the soil, they become almost a part of the soil and respond to changes in the water content of the soil. The amount of water in the blocks determines electrical resistance; thereby, measurement of any change in resistance is an indirect measure of soil water if the block is calibrated for a particular soil.

Nylon and fiber-glass blocks are more sensitive in the higher ranges of soil water than plaster of Paris blocks, but often their contact with soil that is alternately wet and dry is not very good. Nylon blocks are most sensitive at a tension of less than 2 atmospheres. Plaster of Paris blocks function most effectively at a tension between 1 and 15 atmospheres; fiber-glass blocks operate satisfactorily over the entire range of available water. A combination of fiber glass and plaster of Paris provides sensitivity in both the wet and dry ranges and provides good contact between the soil and the unit.

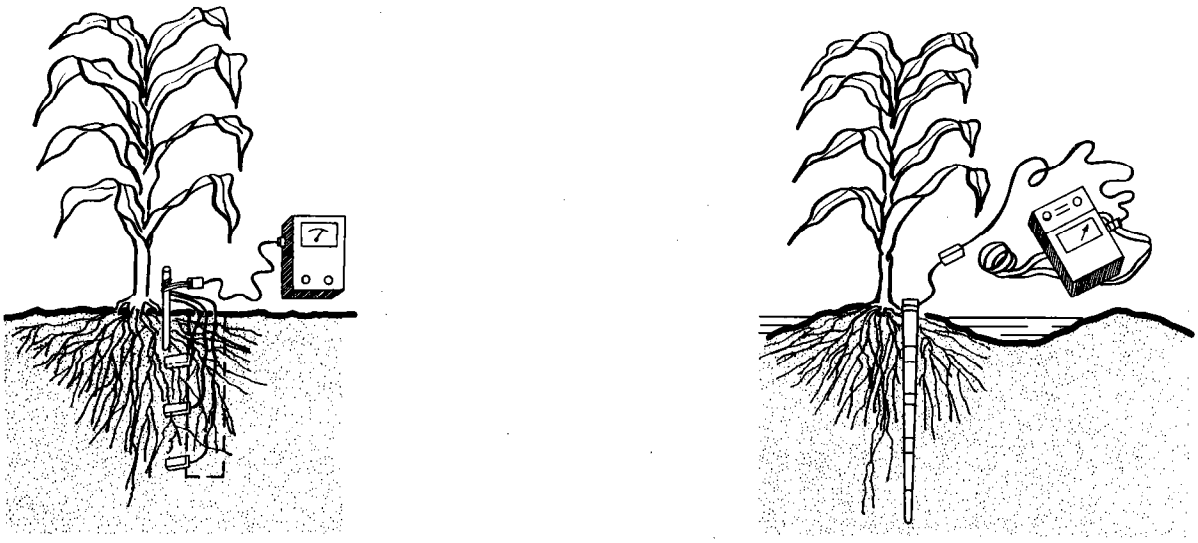
There may be a lag between the soil water change and that in the block, especially in sandy textured soils. This is particularly true with gypsum blocks. Lag times of 1 to 3 days have been measured.

Electrical-resistance instruments are sensitive to salts in the soil; fiber-glass blocks are more sensitive than plaster of Paris. Electrical resistance readings, therefore, are also affected by concentrations of fertilizer. Where fertilizer is spread in bands, electrical-resistance instruments should be placed well to one side of the bands. Temperature affects readings in all units.

In some units calibration drift has caused changes of as much as 1 atmosphere of tension in a single season. The magnitude of a change depends on the number of drying intervals and the number of days between each. Readings

Figure 1-13.

Electrical Resistance Soil Water Meters



also vary with soil type. The same reading may indicate different amounts of available water for different soil textures; therefore, the instrument must be calibrated for the soil in which it is to be used.

If readings are to be representative of an area, the blocks must be properly installed. Individual blocks must be placed in a hole, which disturbs the soil. If the soil is not replaced in the hole at the same density and in the same way as in the rest of the profile, the root development and moisture pattern may not be representative. A good method is to force the blocks into undisturbed soil along the sides of the hole dug. For placement of the blocks, see figure 1-13. In one type, the blocks are cast in a tapered stake. A tapered hole, the same size as the stake, is bored into the ground with a special auger. The stake is saturated with water and then pushed into the hole so that close contact is made between the stake and the soil.

Most of the commercial instruments give good indications of soil water content if they are used according to the manufacturers' instructions. For good results, however, the blocks must to be calibrated in the field for each job. Experience and careful interpretation of instrument readings are needed to get a good estimate of soil-water conditions.

Neutron Scattering—The neutron scattering procedure to estimate soil-water content has gained wide acceptance. It has some advantages over the gravimetric method because repeated measurements may be made at the same location and depth, thus minimizing the effect of soil variability on successive measurements. It also determines water content on a volume basis, the volume of soil involved being influenced by soil type and wetness by the particular instrument used. Disadvantages are the initial high investment in equipment, Federal operating regulations, and the time required per site to install access tubes.

A source of high energy, or fast neutrons, is lowered to the desired depth into a previously installed access tube. The fast neutrons are emitted into the soil from an americium-beryllium or radium-beryllium source and gradually lose energy by collision with various atomic nuclei. Hydrogen, present almost entirely in soil water, is the most effective element in the soil to slow down the neutrons. Thus, the degree of the slowing down of neutrons is a measure of the soil-water content. The slowed, or thermalized, neutrons form a cloud around the source and some of these randomly return to the detector, which causes an electrical pulse on a charged wire. The number of such pulses is measured over a given interval of time with a scalar, or the rate of pulsation can be measured with a ratemeter. The count rate is approximately linearly related to the water content.

When not in use, the radiation source is housed in a shield that contains a high hydrogen material, such as polyethylene or paraffin wax. This material serves as a standard by which proper operation of the instrument can be verified. Inasmuch as instrument variations and source decay take place, it is more satisfactory to use the count ratio method rather than just a count. The ratio of sample count to standard count is plotted versus water content. This eliminates any systematic errors that the instruments may introduce from day to day. The volume of soil measured depends upon the energy of the initial fast neutrons and upon the wetness of the soil. With the radium-beryllium source the volume of soil measured is a sphere of about 6 inches (15 centimeters) in diameter in a wet soil and up to 20 inches (50 centimeters) or more in a dry soil. Measurements near the surface may not be accurate because neutrons may be lost through the surface. It is difficult to accurately detect any sharp change in soil water with depth caused by a wetting because the sphere of influence integrates individual layers.

The manufacturer usually supplies a calibration curve, but one should verify whether it can be used for a given soil. Standard procedures have been developed by SCS for calibrating neutron gauges for a specific soil site.

Heat Dissipation—Heat conductivity can be used as an index to water content using the principle that heat is conducted much faster in water than in dry soil. A constant current may be passed through a heating element imbedded in a porous block for a given time. The resulting heat is conducted away from the element, and the temperature of the element can be related to the water content of the porous block. Temperatures can be measured with a linear diode temperature sensor which eliminates the need to correct for ambient temperature changes. This system is being used to control irrigation in order to maintain soil matric potential within a narrow range. The combination of the heating element and temperature sensor is referred to as a soil water potential sensor. These sensors have essentially been a research tool, although on a limited basis they are being used for field applications. They are available commercially and are being incorporated into irrigation controllers.

Sampling Error

Error of sampling has long plagued irrigators as they seek to determine the amount of water in the soil. Obtaining representative samples is a major problem. Uneven growing of plants and nonuniform root penetration must be considered, because they cause variations of soil water content. Texture and structure variations of soils alter the intake, transmission, and retention of moisture. Variations in land-surface configuration affect the opportunity for intake of

rainfall and irrigation water, and the shapes and sizes of furrows alter the rate of intake of irrigation water. All of these factors cause the water content to vary from point to point in a field. To obtain a representative soil water sample requires that several samples be taken, unless the method determining soil water inherently integrates a large volume of soil. The number of samples required to obtain a representative sample increases as the soil water variation increases.

Another factor which adds to the complexity of measuring soil water is that essentially all methods of soil water determination are based upon small samples. Individual samples can be expected to vary at least 20 percent, plus or minus, from the mean of a large number of samples.

Location of Soil Water Measurements

The location of any soil water measurements is highly important. Selection of places that will give a good estimate of the soil water level over a field generally is a matter of knowing the soil, previous experience, and good judgement. Locating the places for examination is not so difficult in fields of the same soil type as in fields of different soils.

It is generally recommended that one location be near the side of the field where irrigation is to be started as a reference point for starting the irrigation cycle. At least one location should be at the opposite end of the field to determine if the field is being covered fast enough to maintain an adequate soil water level there. Measurements should be made at other locations as indicated by any critical condition in the soil, such as an area that dries out first or stays wet longest. It is good practice to have at least two measurement stations in each critical area and possibly two or three stations in areas that are typical of most of the field. An adequate system of soil water measurement provides the irrigator with enough data to manage the system so that the soil water level is controlled over the entire field. This kind of information serves as a guide in varying both the amount and the frequency of irrigation for different locations in the field or for different periods in the growing season.

In sprinkler irrigation, the measuring stations should be between the sprinkler heads and 10 to 15 feet away from the lateral line. For row crops, measurements should be made in the row or near the plant but not in the bottom of the furrow. For trees, measurements generally are made 4 to 6 feet from the trunk and inside the drip line.

Measurements should be made in that part of the soil from which plant roots extract their water and according to the water-extraction pattern of the particular crop. In uniformly textured soils, one measurement should be made in the upper quarter of the root zone, and one to three more measurements should be made at lower levels. If the maximum water-extraction depth for a given crop is 24 inches, for example, measurements probably should be made at about 6, 12, and 18 inches. For stratified soils, measurements should be taken from the various textural strata. To predict when to irrigate during the early stages of root development, the 6-inch measurement is all that is needed for most crops. As the root system reaches maturity, measurements from all three locations are needed for a clear picture of the water content throughout the water-extraction zone. Sum the water for each measurement to obtain the total soil water content for the profile.

By definition, movement of water from the surface into the soil is infiltration. Water enters the soil through pores, cracks, worm and decayed root holes, and through cavities introduced by tillage. Infiltrated water may evaporate from the soil surface or may be transpired by the plants or may percolate downward beyond the plant roots and contribute to the ground water.

Water applied to the soil by precipitation (natural or man-made, such as sprinkling systems) infiltrates; and some of the water may be stored temporarily on the soil surface if the soil is unable to absorb it. Thus, if the rate of application exceeds the infiltration rate, water collects on the surface, and either ponding takes place or the water runs off. The infiltration rate governs the amount of water entering the soil and the amount that can be stored in the soil profile to be available for crops. In addition, the infiltration rate governs the amount of potential runoff and its associated soil erosion threat. As an example, surface sealing or crusting can reduce infiltration, increase erosion, and limit the available water for plants.

Percolation

The infiltration rate is limited by the ability of the soil to transmit water away from the soil surface through the soil profile when the surface is ponded. This movement of water through the soil profile is known as percolation. Percolation rate is governed by the permeability of the soil or its hydraulic conductivity. Both terms describe the ease with which soil transmits water.

Because water percolates chiefly through large pores in a soil, percolation depends on the relative number and continuity of these pores. Soil with high porosity and coarse open texture has high hydraulic conductivity. For two soils of the same total porosity, the soil with small pores has lower conductivity than the soil with large pores because resistance to flow is greater in small pores. Soil with pores of many sizes conducts water faster if large pores form continuous paths through the profile. In fine-textured soils, conductivity depends almost entirely on the pore space between structural units. In some soils, particles are cemented together to form nearly impermeable layers commonly called hardpans. In other soils very finely divided or colloidal material expands on absorbing water to form an impervious gelatinous mass that restricts water movement.

Quality of water transmitted, particularly its salinity and alkalinity, may have a marked effect on hydraulic conductivity. Change in the viscosity of water has an effect. Chemical change in water may affect hydraulic conductivity greatly without changing viscosity. The addition of even small amounts of sodium chloride to the soil water, insufficient to make any noticeable difference in viscosity, may affect soil structure so much that hydraulic conductivity is greatly reduced.

Factors Affecting Infiltration

Soil Water Content

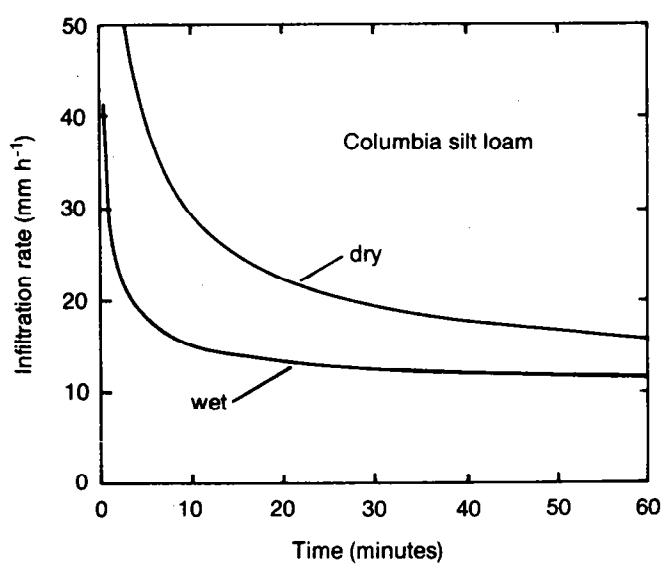
Residual soil water content influences the rate water enters the soil under ponded conditions (fig. 1-14). In dry soils, large differences in matric potential drive water into the soil profile and soil is able to store more water than if the soil were initially wet. The surface soil, however, gradually becomes saturated as irrigation continues and the intake rate decreases to the steady infiltration rate, whether the soil was initially wet or dry.

Soil Sealing

Infiltration may be limited by any restriction to flow that is caused by a change in hydraulic conductivity or a restriction at the soil water interface. Formation of a thin compact layer on the soil surface rapidly reduces the rate of water entry through the surface. This layer results from a breakdown in soil structure that is caused by the beating action of raindrops or the drops from sprinkling systems and by the

Figure 1-14.

Predicted Infiltration Rates for a Deep Columbia Silt Loam With Different Initial Water Contents



action of water flowing over the soil surface. Fine particles, fitted around larger particles, form a relatively impervious seal. Light cultivation before irrigation can help break the seal and increase infiltration. Sealing can be partly prevented by protecting the soil surface with a mulch or some other permeable material. Grasses or other close-growing vegetation intercept droplets, dissipate their energy, and reduce surface sealing.

Surging

During surge irrigation, the intermittent wetting of the soil surface by cycling of flow reduces infiltration. Several mechanisms to explain the reduction in infiltration have been suggested. Wetting and drying allows water to soak and dissolve clods and thereby settle and compact the soil on dewatering. In conjunction with dissolving, a seal may also form as water flows along the surface. Thus, both compaction and sealing reduce infiltration. Air entrapped during dewatering has also been suggested as a reason for reduced infiltration. Water traps air bubbles that block small pores of the soil surface and reduces infiltration. Soil swelling, because of the hydration of clays and the reduction in hydraulic gradient as wetting of the soil progresses, have been suggested as mechanisms for reducing infiltration.

Compaction

Tillage operations may cause compaction and formation of plowpans below cultivation depth if soils are tilled when too wet. A plowpan impedes water movement and thus reduces the infiltration rate. For some soils, infiltration rate is reduced in furrows where tractor wheels travel. Deep tilling, or subsoiling, helps improve water movement for a time by breaking up the impermeable sublayer. The enlarged openings improve water movement. If there are no changes in cultural practices, such as reduced tillage, addition of crop residues, reduced tillage operations, or proper timing of tillage operations, compaction will be reestablished.

Tillage

The infiltration rate may be temporarily increased by plowing, cultivation, or any other stirring that increases pore size in the soil. The beneficial effect of cultivation on soil porosity and intake lasts only until subsequent precipitation or flooding or compaction settles the soil to its former condition. The infiltration rate of loose, porous sand is not likely to increase by tillage operations. Cultivation may reduce intake by compaction and interrupting soil pore space.

Soil Cracking

Cracks form as water is removed from some clay soils. During flood irrigation, cracks fill rapidly before the soil swells; which provides a high initial intake rate. The cracks swell and eventually close as the soil wets. Intake on these fine-textured soils, thereafter, is often negligible or extremely slow. Thus, the amount of water that is applied should be based on crack size and number. Under sprinkler irrigation, if the water application rate is less than the infiltration rate, the application amount is related to the duration of irrigation, not to the crack size and number.

Organic Material

Porosity remains high for comparatively long periods when organic material is made available by the production of high residue crops. Infiltration rate can be maintained and even increased by using a cropping system that provides for high rates of crop residues in the upper few inches of soil. Grasses and legumes are examples of crops which increase the organic matter content of soil. The proportion of stable soil aggregates is increased to create larger pores and, consequently, greater infiltration rates. Perennial crops, such as alfalfa, also improve infiltration by protecting the soil surface from sealing, by maintaining organic matter in the soil, and by increasing the water-conducting pores formed by decayed roots.

Salts in Soil

Salts contained in irrigation water accumulate in irrigated soils and may change soil properties. This accumulation is serious in arid regions where the majority of water is supplied by irrigation. It is often necessary to overirrigate (leach) periodically to manage, reduce, or remove soluble salts from the soil in the root zone area. Rainwater, percolating through the soil in humid areas, leaches out most soluble salts.

Some soluble salts in irrigation water, such as potassium nitrate, may benefit crops directly. Under some conditions, calcium and magnesium have a positive effect on the physical properties of soil. High concentration of sodium chloride or sodium sulfate, however, have a detrimental effect. Soil structure breaks down and eventually soil colloids are dispersed, which reduces tilth and the infiltration rate. This type of sealing may be noticeable even on some sandy soils.

The physical properties, such as infiltration, of some sodic soils can be improved by adding chemicals or soil amendments through which exchangeable sodium is replaced by calcium. Calcium sulfate, gypsum, is a comparatively economical and often used amendment to improve infiltration and aeration in order to enhance root development and plant growth. Other chemicals, such as sulfur and aluminum sulfate, are also used if adequate calcium is available in the soil.

Sediments in Irrigation Water

Fine silt and clay particles carried in suspension affect the quality of irrigation water. Whether this is detrimental or beneficial depends on the amount of silt transported, the length of time the silty flow continues, and the texture of the soil to which water is applied. Occasionally, deliveries of silty water may be beneficial on coarse-textured soils inasmuch as the sediments improve the physical condition of the root zone and reduce the rate of water movement. Silty water applied to fine-textured soil generally adds to the surface sealing problems, because it slows intake and makes the soil difficult to cultivate. Sediments add some plant nutrients, such as potassium, calcium, and phosphate, to the soil.

Soil Erosion

As erosion progresses, the infiltration rate of many soils is reduced because of the loss of surface soil and organic material. This is because less permeable material, such as dense clay subsoil, is uncovered or finer textured subsoil is mixed into the plow layer. In some soils erosion may expose coarse-textured layers, such as sand and gravel, which increases infiltration.

Land Leveling

Moving and mixing of soil during land leveling may change infiltration characteristics. The effects are similar to those of erosion when more or less permeable soil is uncovered. Earth-moving equipment that is used in land leveling may compact the soil, which reduces infiltration. Subsoiling and additions of organic material are often necessary to remedy the problem. In cases where a less permeable layer overlays a permeable layer, the upper layer may be removed to expose the permeable layer in order to improve infiltration.

Temperature

Water intake is greater when it rains in the summer than when it rains in the winter. Apparently, the coefficient of viscosity of water decreases rapidly as temperature increases and this causes more rapid infiltration. Most authorities, however, consider its effect on infiltration negligible.

Surface Storage

Soil surface roughness and slope influence the amount of water which can be collected on the surface and thus be reserved for infiltration. Runoff begins when the application rate exceeds the infiltration rate and surface storage becomes filled. Storage generally is greater on flat, rough, vegetated slopes than on smooth, steep, bare slopes. Thus, surface storage affects the amount of water which infiltrates.

Infiltration Stages

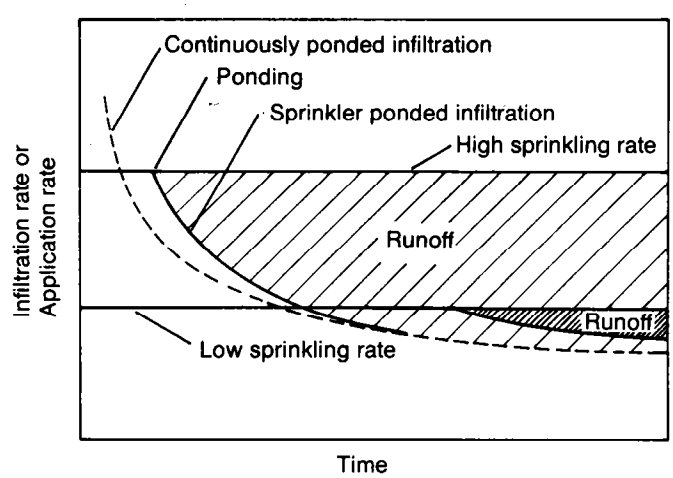
Water does not collect on the soil surface if the precipitation or water application rate from a sprinkler is less than the ability of the soil to absorb water. Figure 1-15 shows the rate at which water enters the soil with time for high and low steady application rates. Early in the process, application rate controls, and is equal to, the infiltration rate; both curves are on the same horizontal line. In time, the ability of the soil to absorb water declines and may be exceeded by the water application rate; in which case, ponding commences and water accumulates on the soil surface. The shaded area between the horizontal steady water application line and the falling infiltration rate curve represents surface storage which may be lost to runoff. Ponding takes place sooner and potential runoff is greater with the high application rate.

The decline in infiltration rate with time under continuously ponded or flooded conditions is the broken line in figure 1-15. At the start of irrigation, the infiltration rate is high but declines rapidly. The infiltration rate is called transient because it changes with time. At the point that the rate changes very little, it becomes the steady infiltration rate. Water will not pond as long as the precipitation rate is less than the steady infiltration rate.

Ponding does not take place when the horizontal, steady precipitation rate line meets the broken continuously ponded line (fig. 1-15). It is later for both high and low application rates; therefore, ponding time and potential runoff are not accurately predicted by superimposing a line that represents

Figure 1-15.

Potential Runoff for High and Low Steady Water Application Rates Similar to Stationary Sprinklers



application rate on a flooded infiltration test curve. In doing so, runoff would be overestimated because ponding takes place later than predicted by the above graphical method. Furthermore, the shape of the three solid curves is slightly different. Thus, ponding time is not accurately predicted by superimposing a line that represents precipitation rate on a flooded infiltration test curve. Runoff may be overestimated because ponding takes place later than predicted by the above graphical method (fig. 1-15).

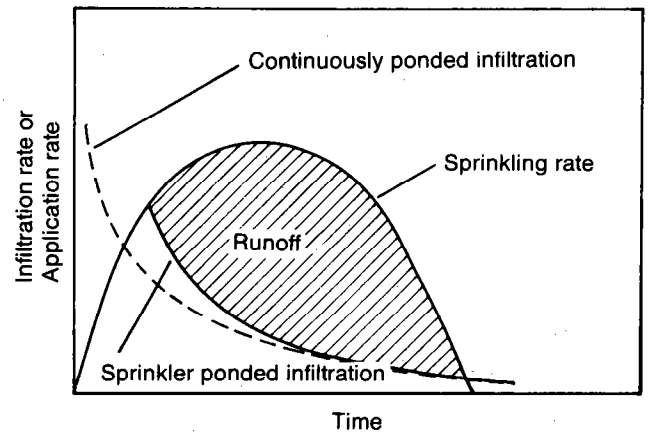
Similarly, ponding time and potential runoff cannot be predicted by superimposing flooded infiltration test curves over water application rate curves for nonstationary sprinklers. As shown in figure 1-16 for moving sprinklers, water application rate at a point increases and then falls rather than being steady as in the case of stationary sprinklers. The infiltration curve follows the water application curve until the application rate exceeds the infiltration rate at which time ponding takes place. Potential runoff is the shaded area between the application rate curve and the solid line representing ponded infiltration under sprinkling. Again, if the dashed line representing continuously ponded infiltration is used, ponding time is too early and potential runoff is overestimated.

Cumulative Infiltration and Infiltration Rate Relations

The time required for a soil to absorb a specified amount of water under ponded conditions can be found by plotting cumulative infiltration with time. This relation is given in figure 1-17 for a high, moderate, and low intake rate soil. The moderate intake rate soil absorbed 3 inches (7.6 cm) of water in about 1.75 hours. Only about one-third of an hour is required to infiltrate 1 inch (2.5 cm), whereas, about 4.5 hours are needed to absorb 6 inches (15.1 cm). Thus, infiltration amount can be controlled by varying application time.

Figure 1-16.

Potential Runoff for Nonstationary Sprinkler



Corresponding plots of instantaneous infiltration rate with time, similar to the one given by the dashed line in figure 1-16, are shown in figure 1-18 for the high, moderate, and low infiltration rate soils. Infiltration rate is high at the start of irrigation, but the rate declines rapidly until it approaches a steady rate.

A comparison of figures 17 and 18 shows that the high intake soil absorbs 3 inches (7.6 cm) of water in about one-third of an hour; at which time intake rate declines to about 4.6 inches (11.7 cm) per hour. In contrast, infiltration rate is 0.3 inches (0.8 cm) per hour for the low intake soil over a total time of 6.5 hours. The relative position on the intake-rate curve, at the time that 3 inches have been infiltrated, differs markedly for the three soils. The infiltration rate declines rapidly for the high intake soil but has approached a nearly stable rate for the low intake soil.

Basic or Steady Infiltration Rate

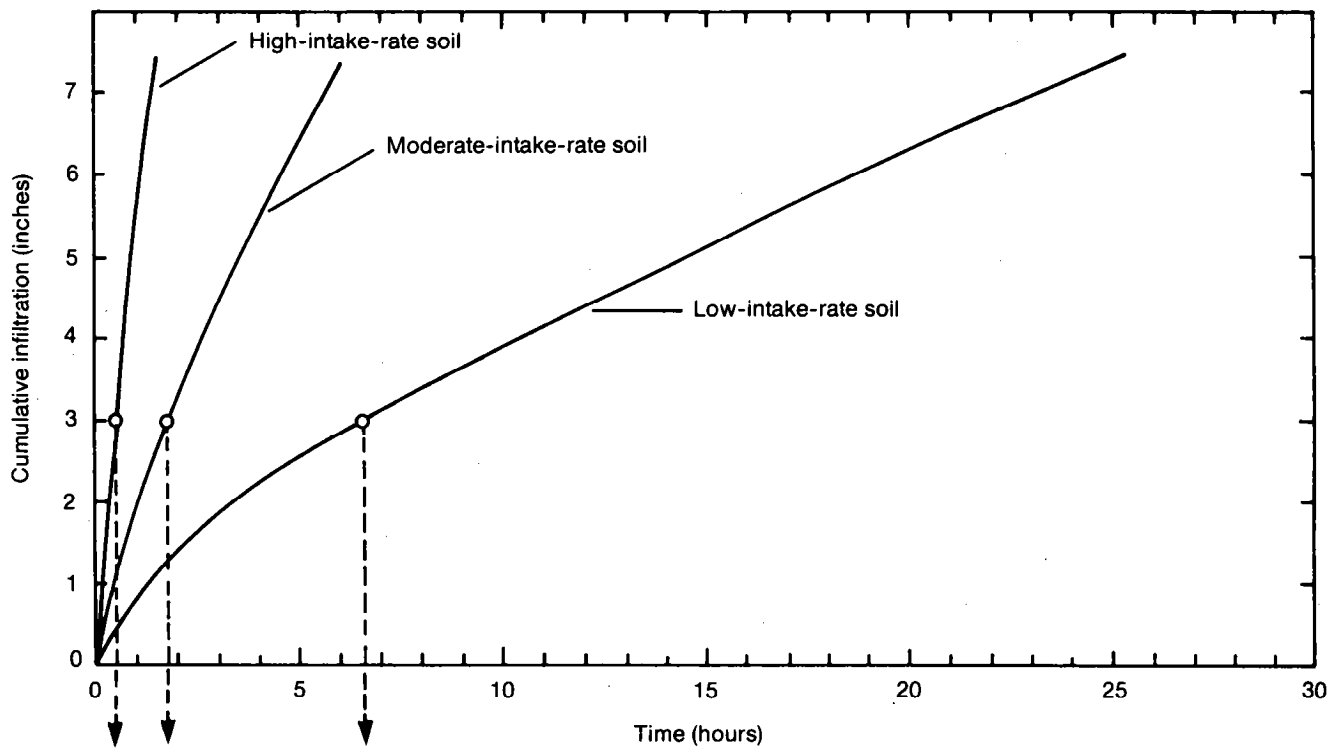
Generally, steady or basic infiltration rate is defined as the nearly constant rate that develops after some time has elapsed from the start of irrigation. The low intake soil shown in figure 1-18 probably would be assigned a basic rate of 0.3 inch (0.8 cm) per hour. Assigning the basic rate to the high-intake soil is more difficult because usually irrigation ceases before the basic infiltration rate is reached. The basic infiltration rate is considered by the Soil Conservation Service to be the point on the curve at which the change in rate is 10 percent. Infiltration rate changes thereafter are considered unimportant.

Seasonal and Spatial Variation

The changes in factors which affect infiltration, discussed above, cause changes in infiltration during the season and from season to season. Infiltration generally decreases during the season from one irrigation event to the next. Reduction in infiltration during the season is usually more significant for an annual crop than for a perennial crop. Season-to-season variation is generally associated with perennial crops because the soil is often cultivated less than annual crops. To meet this changing condition, irrigation management should be flexible so the irrigator can apply

Figure 1-17.

Relation of Cumulative Infiltration to Time for Three Soils



water efficiently. In any case, if the soil is manipulated through tillage or other practices that create larger soil pores, the trend can be slowed or reversed.

Seldom, if ever, do all parts of a field or a soil type have the same ponded infiltration rate because minor variations in soil and plant properties affect infiltration. The variations may be the result of wheel-traffic compaction or natural changes in soil texture and structure.

Spatial variation in infiltration properties is more critical for irrigation systems in which the surface is flooded than for sprinkling systems in which application rate controls infiltration rate. Because infiltration rate varies from place to place in surface irrigation, total infiltration will vary even if the time water is ponded is the same across the field. Variations between fields are easier to manage than variations within a field because irrigation systems can be designed for a specific field.

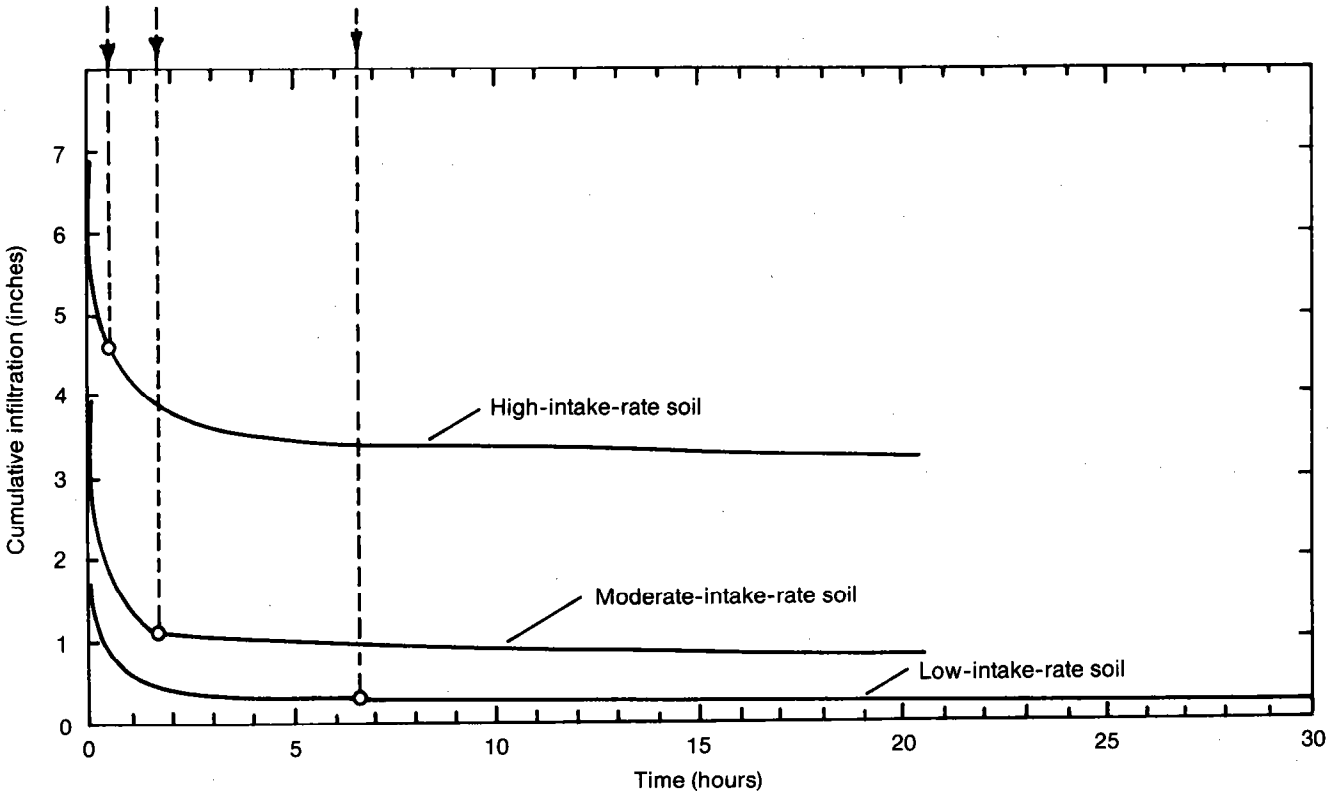
Field Infiltration Measurements

Infiltrometers can be classified as flooding and sprinkling types. Flooding infiltrometers are appropriate for surface irrigation; sprinkling infiltrometers measure infiltration for sprinkler systems. Flooding devices, however, are far more frequently used because they require less equipment and are easier to install and operate than the sprinkling type.

The most common type of flooding infiltrometer consists of a metal cylinder 8 to 18 inches (20 to 45 centimeters) in diameter and 12 to 14 inches (30 to 36 centimeters) in length, which is pressed or driven into the soil. Infiltration is measured by ponding water inside the cylinder and measuring the rate that the free surface falls or by measuring the rate that water must be added to maintain a constant depth of ponding. Once the wetted front exceeds the buried cylinder depth, lateral flow may cause the measured infiltration rate to be higher than would otherwise take place during irrigation. Lateral flow is especially troublesome if restrictive

Figure 1-18.

Relation of Infiltration Rate to Time for Three Soils



layers, such as plow pans, exist or if the hydraulic conductivity decreases with depth. When restrictive layers are at a shallow depth, the infiltration cylinder should be driven into or through the layer if possible. Another means of preventing erroneous measurements because of lateral flow is to use a guarded ring or buffer area around the outside of the infiltration cylinder. Water is ponded between the two cylinders at all times to prevent edge effects and to maintain vertical flow below the central infiltration cylinder.

Infiltration under furrow irrigation involves soil water movement in both vertical and horizontal directions. Because the rate of infiltration depends on the size and shape of the furrow, the rate water moves into the soil is often called the intake rate rather than the infiltration rate. Regardless of the term used, the determination of intake rate is important to the design of an efficient furrow irrigation system. Infiltration rates that are determined by sprinkler or cylinder infiltrometers represent primarily vertical flow, so it is difficult to apply these results directly. One method frequently used to determine intake rates is to make inflow and outflow measurements in an irrigation furrow. Measuring flumes or orifices are used to make flow measurements at two points in an irrigation furrow that are located 30 to 90 feet apart. Intake rates are computed from the difference of inflow and outflow for various times after water application begins. Although this method provides a good means of evaluating existing furrow irrigation systems, it is often not convenient to use this method to determine intake rates for the design of new systems. To avoid this problem, a furrow infiltrometer to measure intake rates in a short section of an irrigation furrow was developed. The furrow is blocked off by metal plates, and water is applied at a rate sufficient to maintain a constant depth. Intake rate is then determined in a manner similar to that described for cylindrical infiltrometers.

Ring and blocked furrow infiltrometers may not simulate actual conditions accurately because water is stagnant, not flowing. To circumvent this problem, a recirculating or flowing furrow infiltrometer may be more appropriate. Water is introduced at one end of a blocked furrow test section and is collected at the other end by a small sump pump and recirculated. Additional water from a supply

reservoir is supplied to the furrow to replace the water that has infiltrated. Infiltration is measured by a change in the water-supply reservoir volume versus time.

Sprinkling or spray infiltrometers usually consist of a plot surrounded by partially buried sheet metal barriers with facilities for measuring the rate of surface runoff. Water is sprinkled onto the surface of the plot at a constant rate or intermittently, as with a rotating sprinkler. If a constant application rate is applied, infiltration rate with time is determined from the recorded runoff measurements by subtracting runoff rate from application intensity. Storage rate should also be considered to avoid significant errors. In the case of a rotating sprinkler, design infiltration rate (not the intake rate with time relation) is taken as the rate where the applied water just disappears from the surface as the sprinkler jet returns to apply more water to the same location. An advantage of the last method is that the infiltration measurements are made for conditions very similar to those that will exist during an actual irrigation.

Models

Attempts to characterize infiltration for field applications have usually involved simplified concepts which permit the infiltration rate or cumulative infiltration volume to be expressed algebraically in terms of time and certain soil properties. The most obvious characteristic of the infiltration process is that the rate decreases rapidly with time during the early stages of the event. One of the most common and simple algebraic expressions is the Kostiakov equation:

$$f = kt^{-a}$$

where f is infiltration rate, t is time after irrigation starts, and k and a are constants which depend on soil and initial conditions.

Although simple, it cannot be adjusted for different field conditions, such as initial water content; moreover, it predicts an infiltration rate approaching zero at long times, which is known to be incorrect. A constant term can be added to correct the latter problem to give the extended Kostiakov equation:

$$f = kt^{-a} + f_c$$

where f_c is the final, constant infiltration rate. Horton presented another three-constants infiltration equation:

$$f = f_c + (f_o - f_c)e^{-bt}$$

where f_o is the infiltration rate at time = 0, and b is the soil constant which controls the rate of decrease of the infiltation rate. Again, the equation parameters are usually evaluated from experimental infiltration data.

Philip proposed that the first two terms of a series solution for infiltration from a ponded surface into a deep homogenous soil be used as a concise infiltration equation as:

$$f = 0.5St^{-.5} + C$$

where S and C are constants which can be related to soil characteristics. S can be adjusted for initial water content; and, similar to the extended Kostiakov equation, a regression fit to experimental data will tend to give:

$$C = f_c$$

A similar, more physically based equation evolved from Green and Ampt:

$$f = K_s\,(1 + M_d S_f/F)$$

where K_s is saturated hydraulic conductivity, M_d is the difference between initial and final volumetric water content, S_f is the suction at the wetting front, and F is the cumulative infiltration.

This model assumes that water enters the soil as slug flow, resulting in a sharply defined wetting front which separates a zone that has been wetted from a totally uninfiltrated zone.

Although more physically based models can estimate infiltration from measured soil properties, generally in practice it is easier to measure and fit infiltration data than to measure soil properties. Actual infiltration measurements also tend to lump effects such as heterogeneities, worm holes, and crusting in the equation parameters. This results in more reliable infiltration predictions than if the parameters are determined from basic soil property measurements.

Plant Root Systems

Plant root systems provide the linkage between the soil water and nutrients and the aboveground parts of plants. Two general types of root systems are recognized: fibrous roots and taproots. Cereal grains and other grasses (monocotyledons) have fibrous root systems. Other crops, such as sugar beets and alfalfa (dicotyledons), have taproot systems. The two types are illustrated in figure 1-19.

Fibrous roots are comprised of many slender roots that are similar in length and diameter. The first root appearing from a germinating seed is a seminal or primary root. The seminal root gradually elongates and increases in diameter. Secondary roots develop from the primary root as lateral branches and subbranches. With continued growth, nodal roots arise from the underground stem nodes. Roots may also develop from aboveground nodes such as the brace roots of maize.

In contrast to the fibrous root system, other crop plants have an entire root system subtended by a single taproot (taproot system). Crops, such as alfalfa and sugar beets, have this type of root system. Although a taproot may extend to a considerable soil depth, the major part of the total root system is made up of first order laterals.

Regardless of the basic rooting characteristics of monocotyledons and dicotyledons, the length and complex branching of an intact root system is considerable after a few weeks of growth. Laterals are initiated in the parent root member with primary laterals giving rise to secondary laterals, and so on, until an extensive network is formed under favorable conditions. Typical growth rates for various root class members are:

root axes, 0.8 inch per day;
primary laterals, 0.2 inch per day; and
secondary laterals, 0.04 inch per day.

Root elongation as high as 2.4 inches per day has been reported for maize. In contrast, unfavorable conditions due to climate, soil composition, soil aeration, or soil chemistry may severely restrict root growth and proliferation.

Crop Species Rooting Characteristics

Proper irrigation management requires good information on crop rooting characteristics with both depth development and rooting density being important considerations. An extensive literature search resulted in the compilation of a list of the maximum rooting depth achieved by some 55 plant species reported from 135 field observations (table 1-5). The range in depth achieved within a crop species probably arises from genetic varietal characteristics and less than desirable growth conditions. An effort was made to exclude data that was based on less than desirable growth conditions.

Figure 1-19.

Fibrous Root System of Corn (Left) and Taproot System of Sugar Beet (Right): Both Are Approximately Two Months Old

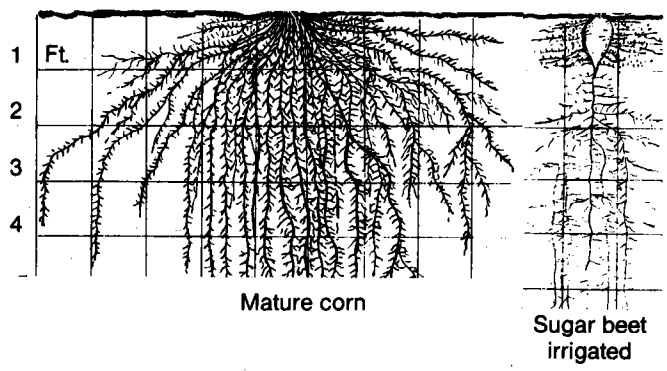


Table 1-5.—*Data source summary of several crop species on the depth development of roots with time and expected maximum rooting depth (RD_m) under favorable environmental conditions (H. Borg and D. W. Grimes, 1986. Depth development of roots with time on empirical description. Transactions of the ASAE. Vol. 29, No. 1, pp. 194-197).*

Crop	No. of Observations	RD_m (cm)
alfalfa (*Medicago sativa*)	7 several (sev.)yrs.	1st yr. 180-240 300-600
asparagus (*Asparagus officinalis*)	1	1st yr. 100-200 sev. yrs. 300+
barley (*Hordeum vulgare*)	7	150-290
sugar beet (*Beta vulgaris*)	1	180-330
broad bean (*Vicia faba*)	1	150-190
bromegrass (*Bromus inermis*)	2	1st yr. 100-140 sev. yrs. 200+
cabbage (*Brassica oleracea*)	1	150-240
carrot (*Daucus carota* var. *sativus*)	1	150-300
cauliflower (*Brassica oleracea*, Botrytis Group)	1	90-150

field corn (*Zea mays* L.)	11	180-300
cotton (*Gossypium hirsutum* L.)	8	150-300
cowpea (*Vigna sinensis*)	1	100-150
cucumber (*Cucumis sativus*)	1	120-180
eggplant (*Solanum melongena*)	1	150-240
flax (*Linum usitatissimum* L.)	1	100-150
garlic (*Allium sativum*)	1	60-100
horseradish (*Amoracia rusticana*)	1	sev. yrs. 300-450
kidneybean (*Phaseolus vulgaris*)	1	100-300
Kohlrabi (*Brassica oleracea*, Gongylodes Group)	1	150-270
leek (*Allium ampeloprasum*, Porrum Group)	1	40-80
lentils (*Lens culinaris Medic*)	1	60-70
lettuce (*Lactuca sativa*)	1	150-250
lima bean (*Phaseolus limensis*)	1	100-200
muskmelon (*Cucumis melo*, Reticulatus Group)	11	100-150
oats (*Avena sativa*)	10	160-260
okra (*Abelmoschus esculentus*)	1	120-160
onion (*Allium cepa*)	1	40-100
parsley (*Petroselinum hortense*)	1	90-150
parsnip (*Pastinaca sativa*)	1	200-300
pea (*Pisum sativum*)	2	100-240
pepper (*Capscium annum* var. *annum*)	1	90-150
potato (*Solanum tuberosum*)	4	50-240
pumpkin (*Cucurbita pepo* var. *pepo*)	1	150-210
radish (*Raphanus sativus*)	2	140-240
rape (*Brussica napus*)	1	200-300
red clover (*Trifolium pratense*)	2	1st yr. 140-180 sev. yrs. 200-300
rhubarb (*Rheum rhaponticum*)	1	sev. yrs. 200-300
rutabaga (*Brassica napus*, Napobrassica Group)	1	150-200
rye (*Secale cereale*)	2	150-240
sorghum (*Sorghum vulgare*)	4	150-300
soybean (*Glycine max*)	22	150-250
spinach (*Spinacia oleracea*)	1	150-200
squash (*Cucurbita pepo* var. *melopepo*)	1	150-240
strawberry (*Fragaria chiloensis*)	1	60-120
sugar beet (*Beta vulgaris* L.)	2	140-200
sugar cane (*Saccharum officinarum*)	3	200-600
sunflower (*Helianthus annuus*)	2	150-300
sweetclover (*Melilotus alba*)	3	1st yr. 150-240 sev. yrs. 300+
sweet corn (*Zea mays* var. *rugosa*)	1	150-180
sweet potato (*Ipomoea batatas*)	1	100-150

Swiss chard (*Beta vulgaris*, Cicla Group)	1	180-240
tomato (*Lycopersicon esculentum*)	1	140-260
turnip (*Brassica rapa*, Rapitera Group)	1	150-200
watermelon (*Citrullus lanatus*)	1	100-150
wheat (*Triticum sativum*)	13	150-300

Factors Affecting Root Growth

Although root growth generally proceeds rapidly under ideal conditions, both the rate of development and the maximum depth to which roots grow can be severely restricted by several factors. Even though crop root systems may be severely restricted, these systems have the capacity to support considerable shoot growth if the effective root system is well aerated and supplied with adequate water and nutrients. The stresses experienced by roots generally fall into categories that include: chemical stress caused by nutrient deficiencies, an unbalanced nutrient supply, or by toxic subtances; physical stress from mechanical impedance, from anaerobic conditions, from lack of water, and from unfavorable temperatures; and biological stresses caused by plant pests and diseases.

Mechanical impedance considerations are responsible for a majority of root limiting situations. These may be genetic in origin for shallow soils that overlie consolidated parent material or pans caused by soil compaction that is associated with certain management systems. Root limitations may be very abrupt with consolidated soil materials or pans or gradual in the case of soil compaction. Soil compaction usually results in reduced root growth rates with total root exclusion only observed in very extreme cases. Compaction of soil reduces the volume occupied by pores, especially those of a large size. This causes mechanical impedance to root extension, lowers the rate of gas exchange between the soil and atmosphere, and changes the water retention and transmission properties of the soil. All of these factors modify root growth and they are affected simultaneously by soil compaction.

Layered soils may offer severe impedance to an expanding root system. The reduced root proliferation of a sand or gravelly layer can be substantial because such layers are usually characterized by high bulk density and strength. These layers are normally well drained, but they are highly rigid as a growing root enters the matrix and expands. A clay layer underlying a medium-textured or sandy soil zone may cause a perched water condition and poor aeration on a transient basis that is restrictive to root expansion through such a layer.

Water Flow Into Roots

Water moves in the soil-plant-atmosphere continuum in response to differences in the potential energy of water in the system. Transpiration causes a lower water potential in the plant shoot and root system than in the bulk soil; consequently, soil water moves into the root system along this potential gradient. Water first enters the root system through epidermal cells in contact with the moist soil, then in turn through cortical cells, the endodermis, pericycle cells, and finally to the xylem that transports the water to the aerial plant parts. The intensity of root development and physical contact between the root and soil are important physical considerations. When the upper part of the root zone becomes comparatively dry and water is available in the lower zone, the uptake of water per unit volume of soil has been observed to be proportional to the rooting density. Thus, the distribution of roots that varies with crop species and soil physical properties becomes an important management concern.

The presence of salts in the soil water solution must be considered when evaluating available water. The plant root contains a semipermeable membrane that allows water to pass but not most of the salt. Therefore, the main effect of soluble salts on plants is osmotic with high salt levels making it difficult for the plant to obtain enough water from the soil solution to meet transpirational demand. Cell enlargement is affected initially, and plants exhibit the typical color changes associated with water stress.

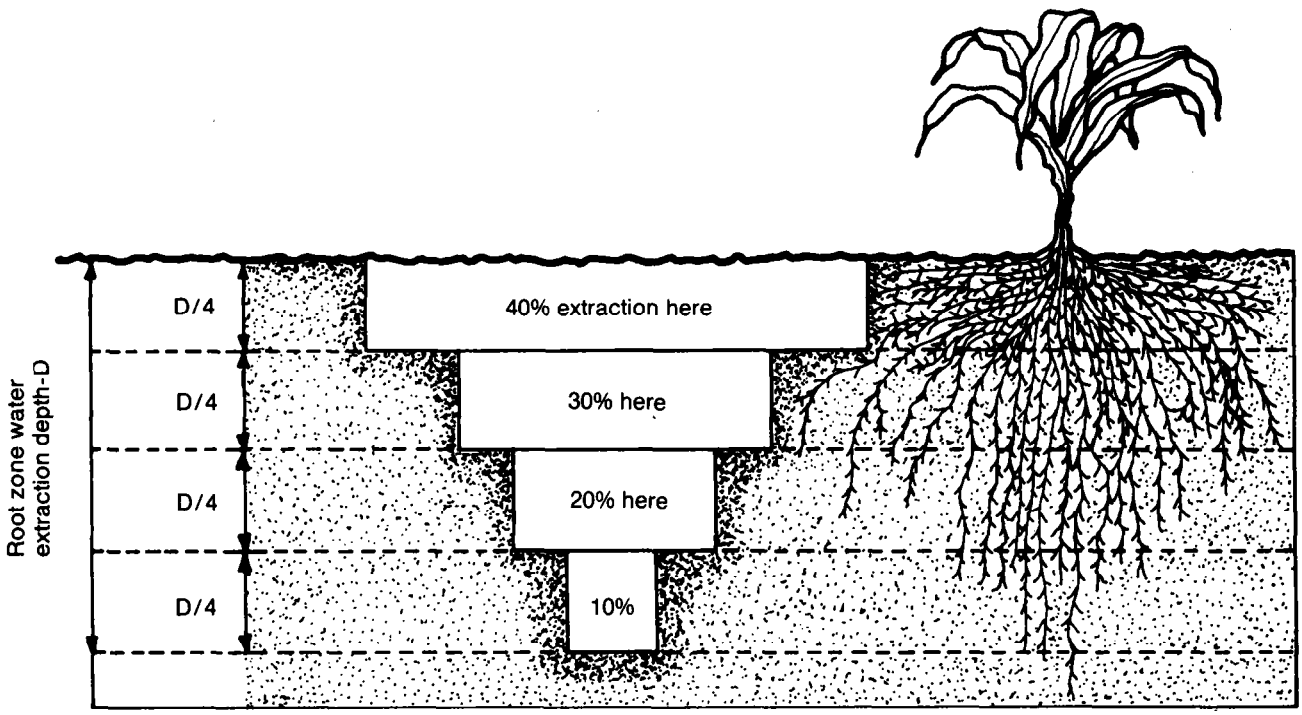
Water Uptake-Root Profile Relations

The root length density (length of roots per unit volume of soil) is generally greatest near the soil surface and declines with increasing depth to the maximum depth to which roots are observed for a given crop species. This general trend is illustrated graphically in figure 1-20.

Extraction of water is most rapid in the zone of greatest root concentration and under the most favorable conditions of temperature and aeration. Because water also evaporates from the upper few inches of soil, water is withdrawn rapidly from the top part of the soil profile. Soils normally show a more rapid loss of water at shallower depths until the potential becomes low enough to be rate limiting. Basic water-extraction curves, based on quarters of the root zone depth, indicate that almost all plants growing in soil that is

Figure 1-20.

Average Water Extraction Pattern of Plants Growing in a Soil Without Restrictive Layers and With an Adequate Supply of Available Water Throughout the Root Zone



uniform and adequately supplied with water have similar moisture-extraction patterns. Figure 1-20 shows that about 40 percent of the extracted water comes from the upper quarter of the root zone, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the bottom quarter. Values for comparative crops are normally within 10 percent of this range. In nonuniform soils, the amount of soil water for crop growth may be determined by the soil layer that has the lowest soil water retention capability. For example, a top soil layer with a low water retention capacity may be rapidly depleted following an irrigation or rain. Even though soil water may be adequate at the lower depths, water stress could be experienced in the early stages of plant development if the root system is not yet fully established. Some examples of limiting soil layers are illustrated in figure 1-21. The normal extraction pattern for a given crop will change when restrictive barriers are encountered. Also, if the water level in the upper soil layers is allowed to remain excessively dry, larger than normal amounts of water will be supplied by the lower soil layers.

Plant Water Use from Shallow Water Tables

Many agricultural production regions are characterized by having a water table close to the soil surface. Upon soil profile drying by evaporation from the soil surface or transpiration from plants, a water potential gradient develops that allows water to move upward in the soil profile and be taken up by plant roots. The magnitude of upward movement will depend on the strength of the water potential gradient that develops, the unsaturated water flow properties of the soil, and depth of the water table. Upward movement for eight North Carolina soils illustrates this phenomenon from values reported in the literature (fig. 1-22).

The practice of subirrigation utilizes this concept; water is introduced to the lower soil profile zones and moves upward into the active root zone by capillarity. Perched shallow water tables in the Central Valley of California contribute up to 50 percent of the total season ET requirement for cotton and seed alfalfa production.

Design Water-Extraction Depth

By definition, the design water-extraction depth is the soil depth used to determine irrigation water requirements for system design purposes. It is the depth to which a reasonably high soil water content should be maintained for optimum production of agricultural crops. It should not be the maximum depth of rooting, especially for long taproot systems, but it is important that it corresponds to the depth at which most of the active plant roots are able to meet transpirational demand. The design depth should be based on local water-extraction data for adopted crops. If two or more plant species with different rooting characteristics are to be grown together, the design depth should be that of the plant having the shallower root system.

The rooting depth of well-established perennials is reasonably stable from one growing season to the next and can generally be considered as constant; however, for annuals, root development depends on time. The researchers who developed table 1-5 formed a functional relationship between relative time and relative rooting depth for annual crops (fig. 1-23). Relative time represents the fractional time lapse to crop maturity from the planting date. Actual rooting depth at a given site and time can be determined by multiplying maximum rooting depth at maturity that is either known or estimated for a specific location by the relative rooting depth determined in figure 1-23.

Evapotranspiration

Evapotranspiration is the process by which water is moved from the surface of the earth to the atmosphere. It consists of the evaporation of liquid or solid water from soil and plant surfaces, plus water that transpires through plant tissues.

Potential ET

The relationship between crop, climate, water, and soil is complex and involves many processes. The processes can be explained somewhat simplistically through a series of concepts and relationships established through research.

Crop water requirement is defined as the depth of water per unit soil area needed to meet the water loss from evapotranspiration (ET_{crop} or ET_c) of a disease-free crop growing in a large field under nonrestricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment

Figure 1-21.

Water Extraction Patterns as Determined by Available Water Content in Various Parts of Soil Profile. Width of Each Profile Represents Total Available Water. Gross Area (Height and Width) of Each Profile Represents Total Available Water in Profile; Hatched Area Shows Water Extraction Pattern for Each Profile.

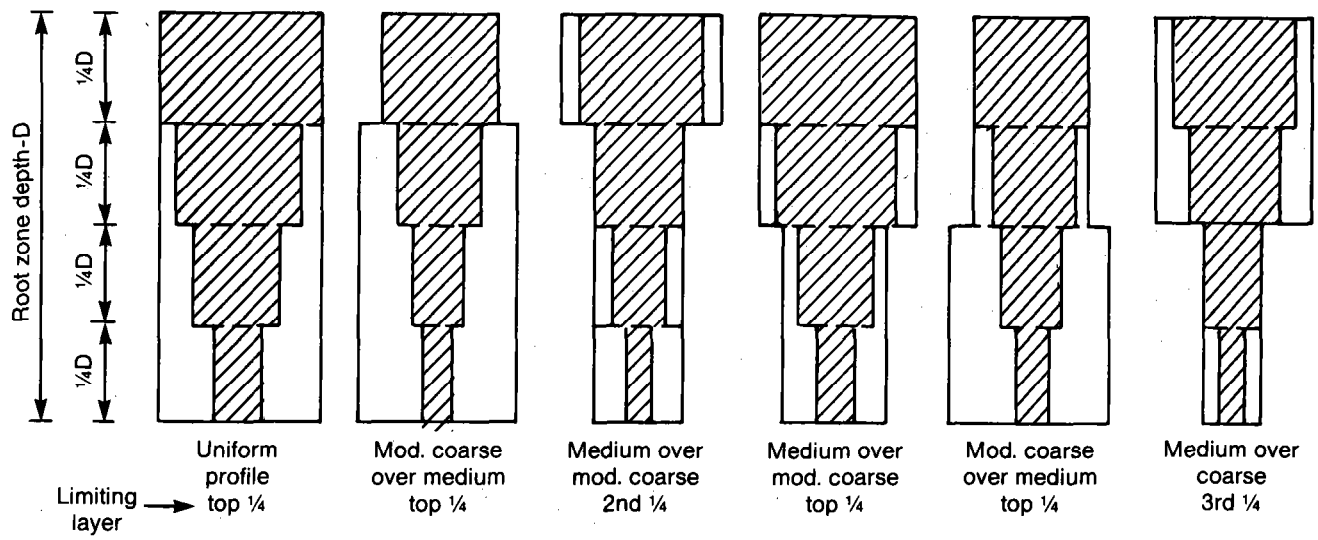


Figure 1-22.

Upward Flux-Water Table Depth Relationships for Eight North Carolina Soils

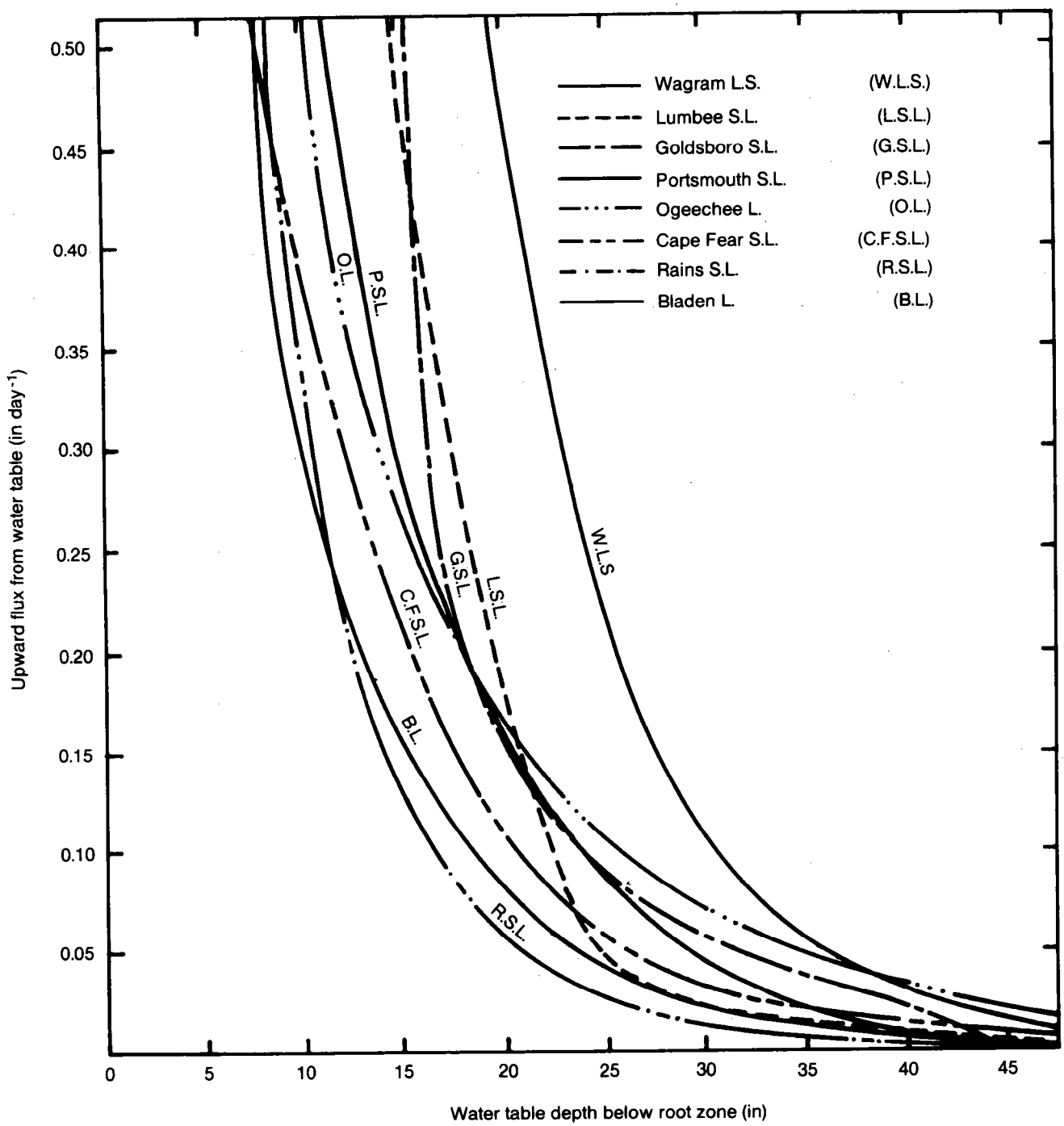
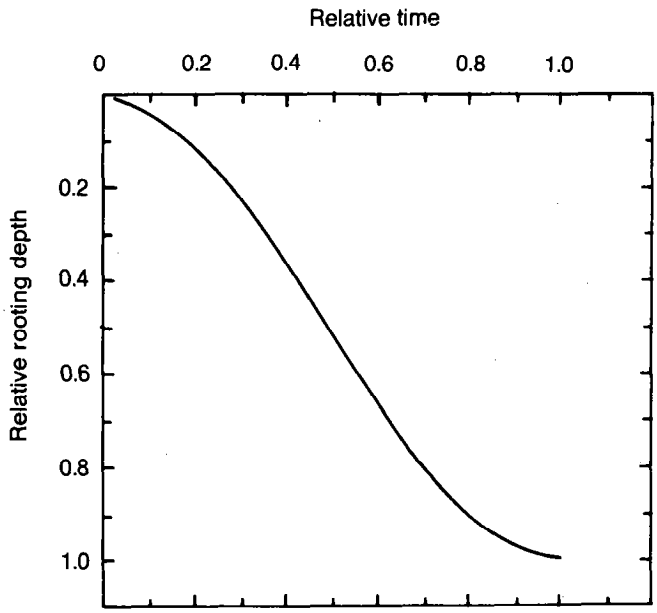


Figure 1-23.

Change in Relative Rooting Depth With Relative Time for Annual Crops



(Doorenbos & Pruitt, 1977). When these conditions are met the crop will produce at the potential or maximum yield (Y_m) and transpire at the maximum rate (ET_m).

Potential ET refers to the maximum ET rate determined by climatic conditions for a specific crop at a specific location at a specific time. Climatic conditions largely determine the potential ET. Various methods, based on meteorological factors, have been developed by researchers to predict the potential ET rates. Solar radiation is the main factor that determines the ET rate; but air temperature, humidity, and wind speed also have an effect.

Direct measurement of ET rates is laborious, time consuming, and requires considerable instrumentation. Therefore, the measurement of climatic factors is most often used to estimate ET based on an equation or model that relates the climatic factors to the ET rate. ET models usually estimate the potential ET of a reference crop such as grass or alfalfa. Conversion factors called "crop coefficients" are used to relate the reference crop ET to the actual crop ET.

Some ET models, such as the pan evaporation and Modified Blaney-Criddle models, relate climatic factors directly to the crop rather than to a reference crop. Crop coefficients are still required to adjust for the plant development stages because the crop transpiration rate is directly related to the canopy leaf area. As the canopy area increases, the crop coefficients must be increased.

When soil water is deficient, the plant is not able to take up enough water to meet the evapotranspiration demand set by the climatic conditions and is said to be under stress. When plants are stressed from soil water deficiency, the actual crop evapotranspiration rate (ET_a) will be less than the potential evapotranspiration rate (ET_m) and the actual crop yield (Y_a) will be less than the maximum yield (Y_m) (Doorenbos & Kassam, 1979). The ET-yield relationship is discussed in detail in a later section.

Predicting Crop ET

Actual crop ET (ET_a), in addition to climate, depends on soil factors and plant factors such as the degree of ground cover, plant leaf characteristics, and surface roughness of the crop canopy. Plant factors are characterized by the crop coefficient that varies during the growing season and according to the model used to estimate ET.

Estimating the actual ET of a growing crop from climatic observations requires the reference crop ET and the specific crop coefficient. The ET of a specific crop is calculated by:

ET_c = (reference crop ET) (specific crop coefficient)

Standard terminology has been established for referring to the various ET models and crop coefficients.

$$ET_c = (ET_o) \quad (K_c)$$
$$ET_c = (E_{pan}) \quad (K_p)$$
$$ET_c = ET_p) \quad (C_{et})$$

Where:

ET_o = Reference ET (approximates 4- to 7-inch tall grass)
ET_p = Potential ET (approximates uncut alfalfa)
E_{pan} = Evaporation from National Weather Service "class A" evaporation pan
ET_c = Evapotranspiration of a specified crop
K_{pan} = Coefficient to convert E_{pan} to ET_o
K_p = Coefficient to convert E_{pan} to ET_c
K_c = Coefficient to convert ET_o to ET_c
C_{et} = Coefficient to convert ET_p to ET_c

Several equations or models are available for estimating reference crop ET. The two reference crops used for estimating crop ET are grass and alfalfa. Grass is the

reference crop most often used and is becoming the standard reference. Care must be used to avoid mixing methodologies and coefficients. The selection of the method to be used may be determined by the available information; however, conversion from one reference base to another can be made by a general factor. If local conversion factors have been determined, they should be used. General conversion factors listed in table 1-6 may be used until specific local factors can be determined.

Generally, the selection of a method to estimate ET will be based on the kind of climatic data available and the degree of accuracy required in determining crop water-use rates. Prediction accuracy will usually be best for those procedures requiring the greatest input detail of climatic parameters. The following are sample methods used for calculating ET: Penman-Monteith (variable canopy height), FAO Blaney-Criddle, FAO Radiation, Jensen-Haise, Pan Evaporation, and SCS Blaney-Criddle. The monthly reference estimates of these procedures, plotted against lysimeter measured ET (ASCE Water Requirements Committee, 1987), are shown in figures 1-24a through 1-24f. All of these methods can be used to determine monthly ET_o, but the SCS Blaney-Criddle method cannot be used to determine daily ET_o for scheduling purposes.

Methods of estimating crop water requirements are discussed in detail in SCS National Engineering Handbook, section 15 : Irrigation, chapter 2 : Irrigation Water Requirements.

Table 1-6.—*General factors for conversion from one method of estimating crop ET to another (Snyder & Dickey, 1982)*

Evapotranspiration		Coefficients	
To ET_o		*To K_c*	
ET_o	$= (E_{pan})(K_{pan})$	K_c	$= K_p/K_{pan}$
	$= (E_{pan})(0.75)$		$= (K_p)(1.33)$
	$= (ET_p)(0.87)$		$= (C_{et})(1.15)$
To Et_p		*To C_{et}*	
ET_p	$= (ET_o)(1.15)$	C_{et}	$= (ET_o)(0.87)$
	$= (E_{pan})(1.08)$		$= (K_p)(0.93)$
To E_{pan}		*To K_p*	
E_{pan}	$= ET_o/K_{pan}$	K_p	$= (K_c)(K_{pan})$
	$= (ET_o)(1.33)$		$= (K_c)(0.75)$
	$= (ET_p)(0.93)$		$= (C_{et})(1.08)$

Crop Coefficient

A crop coefficient is the ratio of the actual crop ET to reference crop ET at a specific time. A plot of the crop coefficient as a function of time is known as a crop curve. An illustration of a crop curve is given in figure 1-25.

Figure 1-25 delineates the time during the growing season as initial, crop development, midseason, and late. Selection of these categories is arbitrary; using calendar days does not account for the possible year-to-year differences in climatic conditions that affect growth rate. The use of accumulated growing degree days, when available for the crop, avoids this disadvantage.

Monthly Reference Estimates From Several Different Procedures Versus Lysimeter-Measured ET

Figure 1-24(a).

Penman-Monteith, Var. Canopy Height

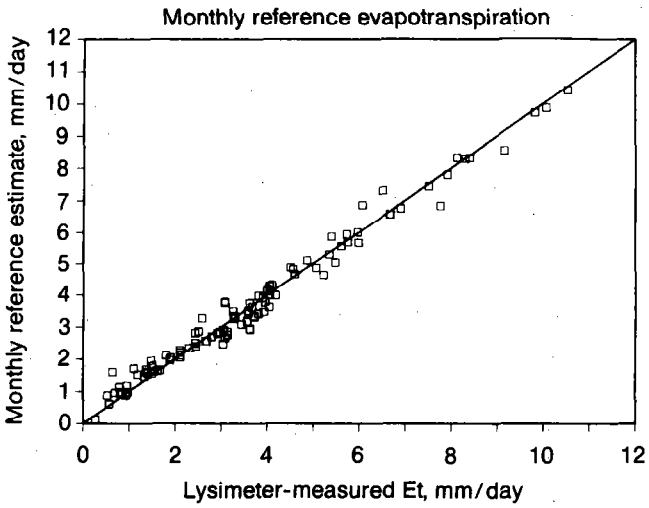


Figure 1-24(b).

FAO Blaney-Criddle

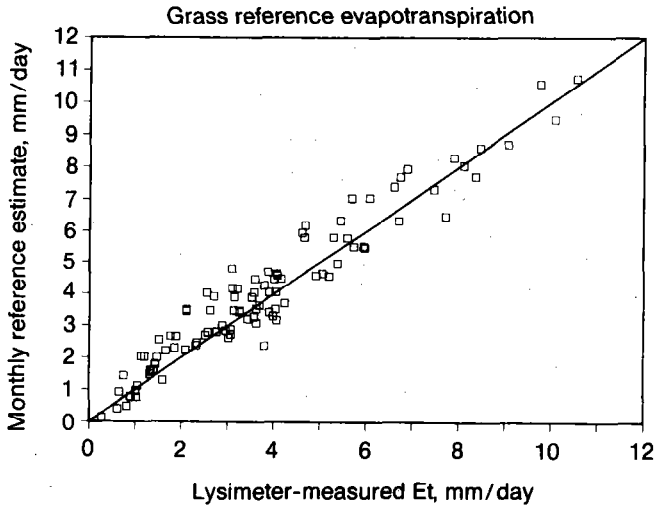


Figure 1-24(c).

FAO Radiation

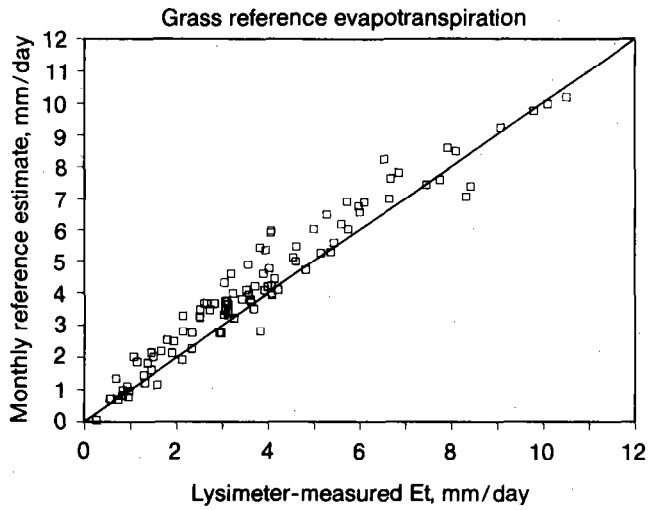


Figure 1-24(d).

Jensen-Haise

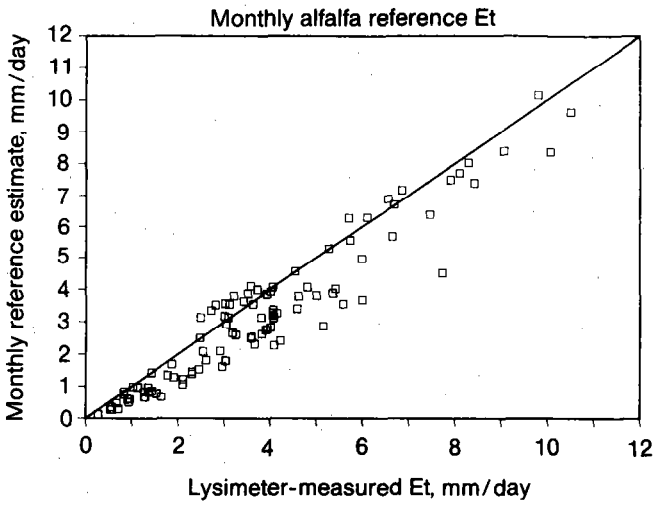


Figure 1-24(e).

Pan Evaporation

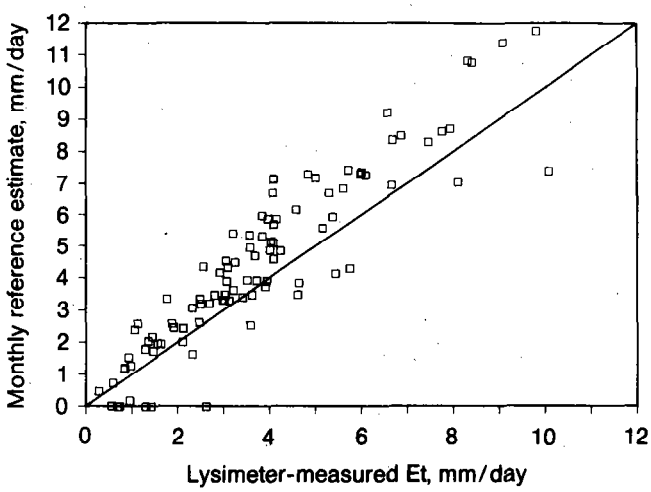
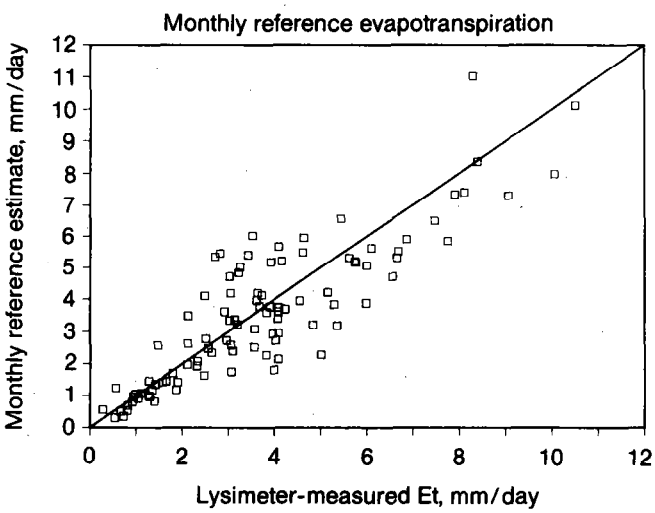


Figure 1-24(f).

SCS Blaney-Criddle (TR-21)



Crop Critical Stress Periods

For many crops there are critical periods during the growing season when a water deficit or stress is detrimental to crop yield. For most crops that have a critical period, the period generally is associated with some stage of reproductive growth; exceptions, however, do take place. The critical period for a number of commonly grown crops under an irrigated culture is given in table 1-7.

Table 1-7.—*Critical periods for water stress, symptoms, and some other considerations for several important crops.*

Crop	Water Stress	Critical Period	Other Considerations
Alfalfa	Darkening color, then wilting	Early spring & immediately after cuttings	Normally 3-4 inches of water needed between cuttings. Fall irrigation is desirable.
Corn	Curling of leaves by mid-morning	Tasseling, silk stage until grain is fully formed	Needs adequate water from germination to dent stage for maximum production.
Sorghum	Curling of leaves by mid-morning	Boot, bloom & dough stages	Yields are reduced if water is short during seed development.
Sugar Beets	Leaves wilting during heat of the day	Post thinning	Excessive fall irrigation lowers sugar content.
Beans	Wilting	Bloom and fruit set	Yields are reduced if water is short at bloom or fruit set.
Small Grain	Dull green color, then firing of lower leaves	Boot and bloom	Last irrigation is at milk stage.
Potatoes	Wilting during heat of the day	Tuber formation to harvest	Water stress during critical period may cause deformation of tubers.
Onions	Wilting	Bulb formation	Keep soil moist during bulb formation, let soil dry near harvest.
Tomatoes	Wilting	After fruit set	Wilt and leaf rolling can be caused by disease.
Cool Season Grass	Dull green color, then wilting	Early spring, early fall	For seed production critical period is boot to head formation.
Fruit Trees	Dulling of leaf color, and drooping	Any point during growing season	Stone fruits are sensitive to water stress during last irrigation.

Yield-Evapotranspiration Relationships

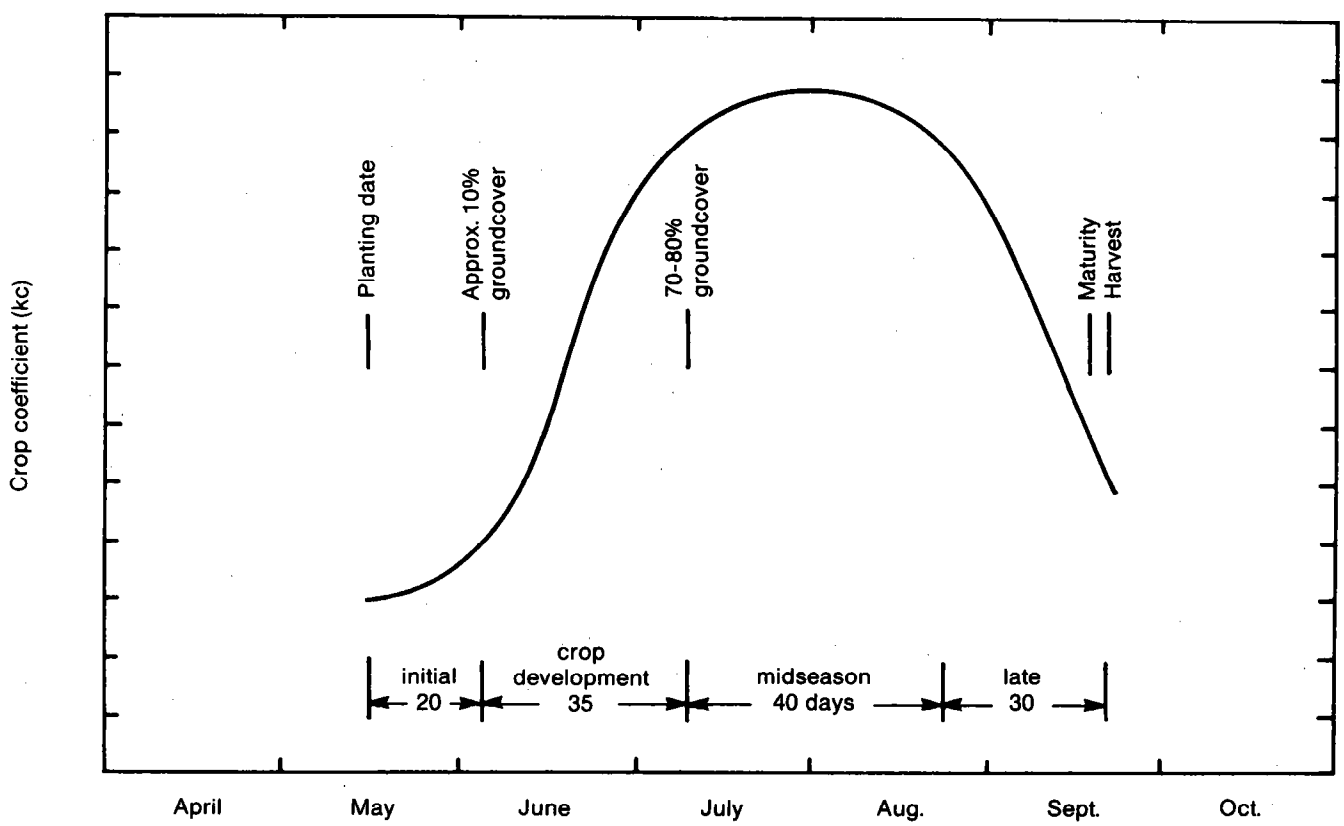
The amount of water evapotranspired to produce the highest crop yield at a given location will depend on the climate, soil, and characteristics of the specific crop. A supply of irrigation water is essential for sustained high levels of crop productivity. In arid and semiarid regions salinity is a potential problem that must be considered at the same time. If a water deficit develops in the soil beyond a threshold level for the specific stage of growth, the resulting water stress will reduce ET, and crop yield will be reduced proportionately. In recent years, recognition of this characteristic has led researchers to establish mathematical functions that characterize this direct relationship. Generally, studies to develop yield-ET functions have been conducted under nonlimiting salinity conditions. This is somewhat unfortunate because it is now usually accepted that the detrimental effects of excess salinity result from a reduction in ET that forms a direct linkage to reduced crop yields. It has been effectively demonstrated that yield-ET and yield-salinity effects can be reduced to a single yield-ET function in the absence of specific toxic ions that manifest yield loss on their own.

Concepts of Production Functions

The production function provides a useful means of analyzing water-productivity relations if the function is based on data that utilize proper irrigation scheduling to give the least yield reduction possible from a defined water deficit. Water response functions for a variety of crops have been developed. Although many variables are used to quantify the amount of water used in the production process, three of the greatest importance are ET, applied water, and soil water. Evapotranspiration has the greatest rigor and potential for transferability between contrasting soils and geographic regions. The amount of applied water, however, is the controlled variable and, in an economic sense, represents the cost consideration. Soil water status provides a link between ET and applied water and is an indication of management and the application uniformity of the irrigation system.

Figure 1-25.

Illustration of a Crop Coefficient Curve

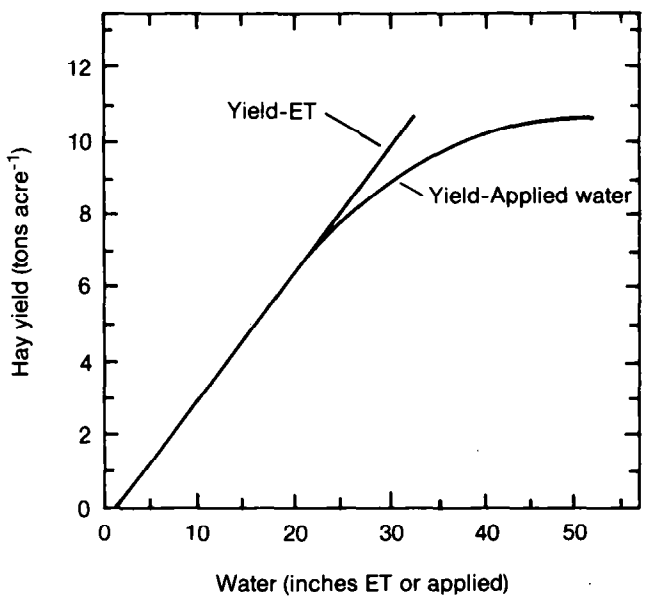


Yield-Evapotranspiration Production Functions

For many crops and growing conditions, the relationship between ET and yield is linear up to ET values that result in maximum productivity; this is especially true for crops where the aboveground biomass represents yield. This type of response is illustrated in figure 1-26 for total growing season alfalfa hay yield and ET in the San Joaquin Valley. Approximately 33.5 inches (85 centimeters) were required to achieve a maximum yield of 10.7 tons per acre (24 metric tons per hectare). Figure 1-27 shows a relationship between cotton lint yield and ET that is nonlinear. The relatively complex nature of vegetative-reproductive growth partitioning of cotton accounts for the slight curvature for this function; however, other crops, such as corn and sorghum, have been shown to have linear functions between seed or reproductive growth and ET.

Figure 1-26.

Alfalfa Hay Yield-ET and Yield Applied Water (AW) Functions for the San Joaquin Valley, California



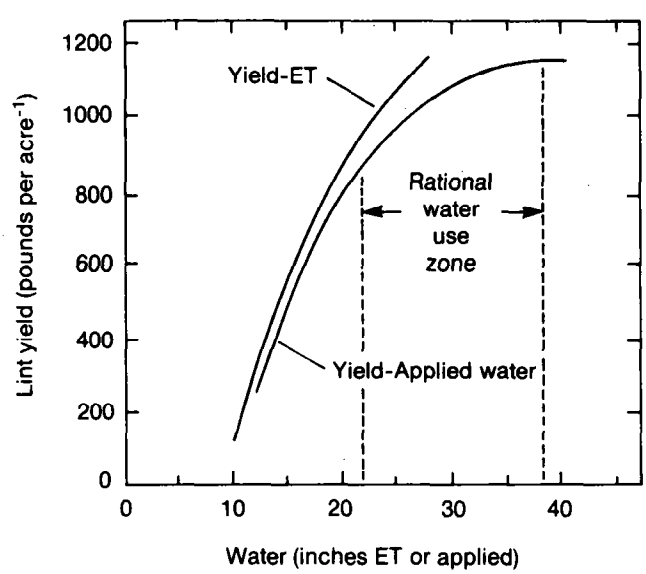
Yield-Applied Water Relationships

Figures 1-26 and 1-27 show that an applied water (AW) function progressively departs from the ET function as ET and applied water increase. This results primarily from increased drainage below the root zone and larger amounts of AW remaining in the soil profile at the end of the growing season which is directly related to the level of management.

The limits of a "rational water use zone" are depicted in figure 1-27. Applied water to achieve maximum yield is the upper limit, and AW required to reach a maximum average product (yield/applied water) is the basis for the lower limit. Applied water to maximize profit always will fall within the limits of the rational input zone. Adding additional water beyond that associated with achieving maximum yield may frequently be associated with yield reduction. Mechanisms that may be responsible for the yield loss include leaching of nutrients, reduced aeration, and excessive vegetative growth at the expense of reproducing seed yield.

Figure 1-27.

Cotton Lint Yield-ET and Lint Yield-Applied Water (AW) Functions for the San Joaquin Valley, California

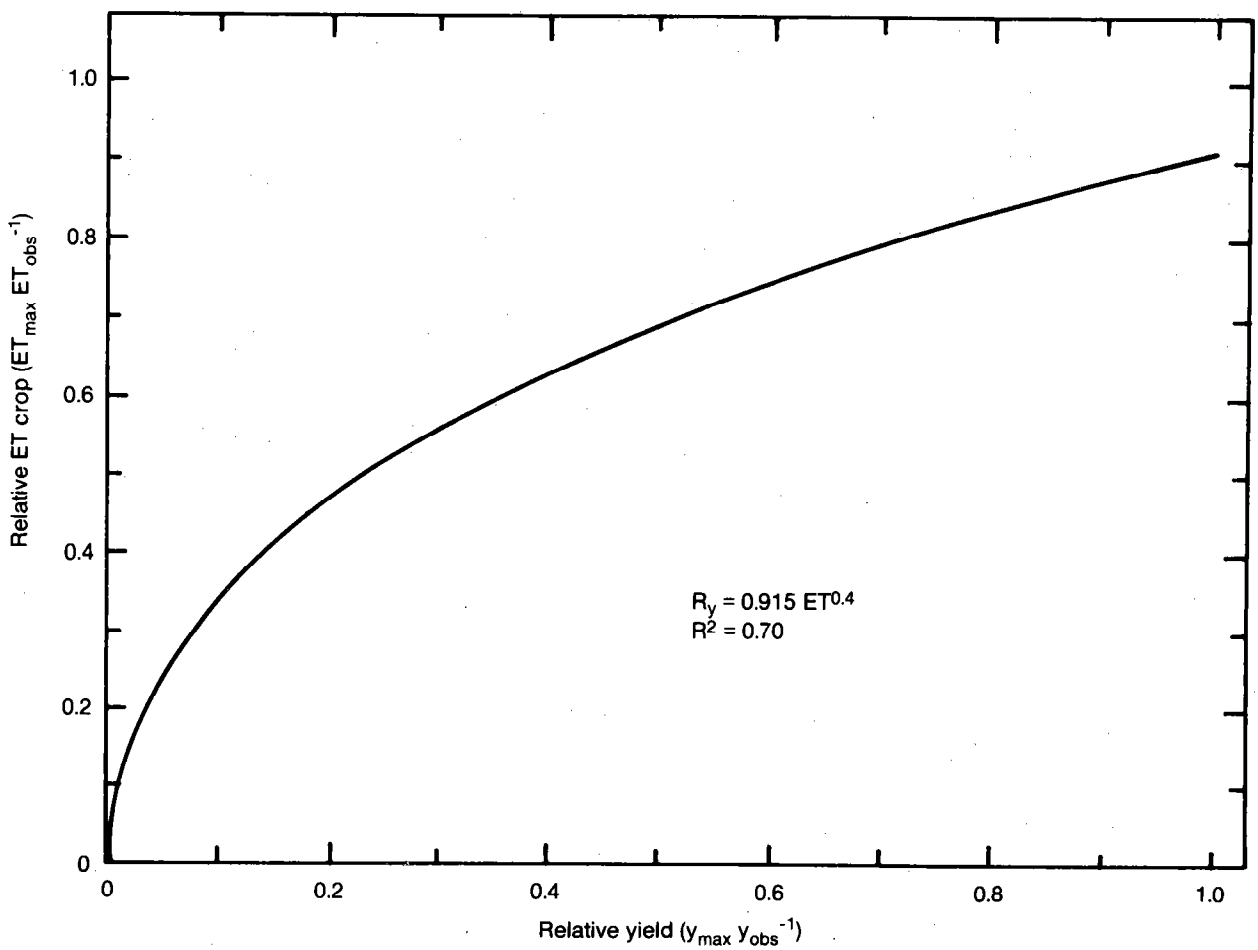


Transferability of Yield-Evapotranspiration Functions

Empirically derived water production functions are usually correct only for the site specific conditions under which they are developed; however, functions which use relative ET (actual ET/potential ET) and relative yield (actual yield/maximum yield) offer some advantage toward a more generalized function. A crop yield-water function for a specific region can be obtained from the dimensionless form by scaling the observed maximum yield and water use required to achieve this yield of a site to the relative values. Research shows that a fair amount of transferability, among geographic regions of contrasting soil and climatic conditions, is possible under this procedure. Figure 1-28 illustrates a dimensionless yield-ET function for Thompson grapevines.

Figure 1-28.

Relative Yield of Thompson Grapes Versus Relative Evapotranspiration



Salinity Effects

Dissolved salts in irrigation water contribute to soil salinity that causes a yield loss to the crop for salinity levels beyond the threshold of tolerance for a given crop. Yield loss is generally associated with reduced plant size and lower ET. For a given amount and salt load of irrigation water, over a lengthy time period, an equilibrium will be established between ET, leaching, soil salinity, and crop yield. Under these conditions, the detrimental effects of salinity are related to crop yield reduction that is associated with the reduced ET.

Generally, crops will tolerate salinity without yield reduction up to a definable threshold level. As salinity increases beyond the threshold level, yields are linearly diminished until crop production is no longer feasible. Table 1-8 uses this concept for four categories of crop sensitivity to soil salinity (EC_e, conductivity of the soil saturation extract); namely, sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). The table gives the threshold values and slope of the linear yield loss function with increased salinity. Although generalized categories of crop salt tolerance can be made, it must be recognized that salt tolerance depends on many plant, soil, and climatic variables. The time-averaged salinity of a root zone is determined by the amount of drying that occurs between rains or irrigations. Both matric and osmotic potentials decline on drying, and it is generally thought that the sum of the two is the total soil water potential that the plant responds to. As soil water is depleted from a soil profile having a nonuniform distribution of salts, the total potential of water being absorbed tends to approach a uniform potential at all depths. Following irrigation or rain, plants absorb water first from root zone regions of low osmotic stress, usually the upper, less saline part of the profile. As matric stress increases in the upper profile, total water stress is equalized on the entire soil profile since more salts are present toward the lower part of the root zone. Frequent irrigation to maintain a high level of soil moisture in the upper profile will maintain a low level of water stress even though considerable salinity may be present in the lower root zone.

Table 1-8.—*Salt tolerance of herbaceous crops (E. V. Maas, 1986. Applied Agricultural Research 1:12-26).*

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name	Threshold dS/m	Percent[1] yield reduction	Rating[2]
Fiber, grain, and special crops				
Barley	*Hordeum vulgar*	8.0	5.0	T
Bean	*Phaseolus vulgaris*	1.0	19.0	S
Broadbean	*Vicia Faba*	1.6	9.6	MS
Corn	*Zea Mays*	1.7	12.0	MS
Cotton	*Gossypium hirsutum*	7.7	5.2	T
Cowpea	*Vigna unguiculata*	4.9	12.0	MT
Flax	*Linum usitatissimum*	1.7	12.0	MS
Guar	*Cyamopsis tetragonoloba*	-	-	MT
Millet, foxtail	*Setaria italica*	-	-	MS
Oats	*Avena sativa*	-	-	MT
Peanut	*Arachis hypogaea*	3.2	29.0	MS
Rice, paddy	*Oryza sativa*	3.0	12.0	S
Rye	*Secale cereale*	-	-	MT
Safflower	*Carthamus tinctorius*	-	-	MT
Sesame	*Sesamum indicum*	-	-	S
Sorghum	*Sorghum bicolor*	6.8	16.0	MT
Soybean	*Glycine Max*	5.0	20.0	MT
Sugarbeet	*Beta vulgaris*	7.0	5.9	T
Sugarcane	*Saccharum officinarum*	1.7	5.9	MS
Sunflower	*Helianthus annuus*	-	-	MS
Triticale	*X. Triticosecale*	-	-	T
Wheat	*Triticum aestivum*	6.0	7.1	MT
Wheat (semidwarf)	*T. aestivum*	8.6	3.0	T
Wheat, Durum	*T. turgidum*	5.9	3.8	T
Grasses and forage crops				
Alfalfa	*Medicago sativa*	2.0	7.3	MS
Alkaligrass, Nuttall	*Puccinellia airoides*	-	-	T
Alkali sacaton	*Sporobolus airoides*	-	-	T
Barley (forage)	*Hordeum vulgare*	6.0	7.1	MT
Bentgrass	*Agrostis stolonifera palustris*	-	-	MS
Bermudagrass	*Cynodon Dactylon*	6.9	6.4	T
Bluestem, Angleton	*Dichanthium aristatum*	-	-	MS
Brome, mountain	*Bromus marginatus*	-	-	MT
Brome, smooth	*B. inermis*	-	-	MS
Buffelgrass	*Cenchrus ciliaris*	-	-	MS
Burnet	*Poterium Sanguisorba*	-	-	MS
Canarygrass, reed	*Phalaris arundinacea*	-	-	MT
Clover, alsike	*Trifolium hybridum*	1.5	12.0	MS
Clover, Berseem	*T. alexandrinum*	1.5	5.7	MS
Clover, Hubam	*Melilotus alba*	-	-	MT
Clover, ladino	*Trifolium repens*	1.5	12.0	MS
Clover, red	*T. pratense*	1.5	12.0	MS
Clover, strawberry	*T. fragiferum*	1.5	12.0	MS
Clover, sweet	*Melilotus*	-	-	MT
Clover, white Dutch	*Trifolium repens*	-	-	MS
Corn (forage)	*Zea Mays*	1.8	7.4	MS
Cowpea (forage)	*Vigna unguiculata*	2.5	11.0	MS
Dallisgrass	*Paspalum dilatatum*	-	-	MS
Fescue, tall	*Festuca elatior*	3.9	5.3	MT
Fescue, meadow	*F. pratensis*	-	-	MT
Foxtail, meadow	*Alopecurus pratensis*	1.5	9.6	MS
Grama, blue	*Bouteloua gracilis*	-	-	MS
Hardinggrass	*Phalaris tuberosa*	4.6	7.6	MT
Kallargrass	*Diplachne fusca*	-	-	T
Lovegrass	*Eragrostis*	2.0	8.4	MS
Milkvetch, Cicer	*Astragalus cicer*	-	-	MS
Oatgrass, tall	*Arrhenatherum, Danthonia*	-	-	MS
Oats (forage)	*Avena sativa*	-	-	MS
Orchardgrass	*Dactylis glomerata*	1.5	6.2	MS
Panicgrass, blue	*Panicum antidotale*	-	-	MT
Rape	*Brassica napus*	-	-	MT
Rescuegrass	*Bromus unioloides*	-	-	MT
Rhodesgrass	*Chloris Gayana*	-	-	MT
Rye (forage)	*Secale cereale*	-	-	MS
Ryegrass, Italian	*Lolium italicum multiflorum*	-	-	MT
Ryegrass, perennial	*L. perenne*	5.6	7.6	MT
Saltgrass, desert	*Distichlis stricta*	-	-	T

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name	Threshold dS/m	Percent[1] yield reduction	Rating[2]
Sesbania	*Sesbania exaltata*	2.3	7.0	MS
Siratro	*Macroptilium atropurpureum*	-	-	MS
Sphaerophysa	*Sphaerophysa salsula*	2.2	7.0	MS
Sudangrass	*Sorghum sudanense*	2.8	4.3	MT
Timothy	*Phleum pratense*	-	-	MS
Trefoil, big	*Lotus uliginosus*	2.3	19.0	MS
Trefoil, narrowleaf birdsfoot	*L. corniculatus tenuifolium*	5.0	10.0	MT
Trefoil, broadleaf birdsfoot	*L. corniculatus arvenis*	-	-	MT
Vetch, common	Vicia angustifolia	3.0	11.0	MS
Wheat (forage)	*Triticum aestivum*	4.5	2.6	MT
Wheat, Durum (forage)	*T. turgidum*	2.1	2.5	MT
Wheatgrass, standard crested	*Agropyron sibiricum*	3.5	4.0	MT
Wheatgrass, fairway crested	*A. cristatum*	7.5	6.9	T
Wheatgrass, intermediate	*A. intermedium*	-	-	MT
Wheatgrass, slender	*A. trachycaulum*	-	-	MT
Wheatgrass, tall	*A. elongatum*	7.5	4.2	T
Wheatgrass, western	*A. Smithii*	-	-	MT
Wildrye, Altai	*Elymus angustus*	-	-	T
Wildrye, beardless	*E. triticoides*	2.7	6.0	MT
Wildrye, Canadian	*E. canadensis*	-	-	MT
Wildrye, Russian	*E. junceus*	-	-	T
Vegetable and fruit crops				
Artichoke	*Helianthus tuberosus*	-	-	MT
Asparagus	*Asparagus officinalis*	4.1	2.0	T
Bean	*Phaseolus vulgaris*	1.0	19.0	S
Beet, red	*Beta vulgaris*	4.0	9.0	MT
Broccoli	*Brassica oleracea botrytis*	2.8	9.2	MS
Brussels sprouts	*B. oleracea gemmifera*	-	-	MS
Cabbage	*B. oleracea capitata*	1.8	9.7	MS
Carrot	*Daucus carota*	1.0	14.0	S
Cauliflower	*Brassica oleracea botrytis*	-	-	MS
Celery	*Apium graveolens*	1.8	6.2	MS
Corn, sweet	*Zea Mays*	1.7	12.0	MS
Cucumber	*Cucumis sativus*	2.5	13.0	MS
Eggplant	*Solanum Melongena esculentum*	-	-	MS
Kale	*Brassica oleracea acephala*	-	-	MS
Kohlrabi	*B. oleracea gongylode*	-	-	MS
Lettuce	*Lactuca sativa*	1.3	13.0	MS
Muskmelon	*Cucumis Melo*	-	-	MS
Okra	*Abelmoschus esculentus*	-	-	S
Onion	*Allium Cepa*	1.2	16.0	S
Parsnip	*Pastinaca sativa*	-	-	S
Pea	*Pisum sativum*	-	-	S
Pepper	*Capsicum annuum*	1.5	14.0	MS
Potato	*Solanum tuberosum*	1.7	12.0	MS
Pumpkin	*Cucurbita Pepo Pepo*	-	-	MS
Radish	*Raphanus sativus*	1.2	13.0	MS
Spinach	*Spinacia oleracea*	2.0	7.6	MS
Squash, scallop	*Cucurbita Pepo Melopepo*	3.2	16.0	MS
Squash, zucchini	*C. Pepo Melopepo*	4.7	9.4	MT
Strawberry	*Fragaria*	1.0	33.0	S
Sweet potato	*Ipomoea Batatas*	1.5	11.0	MS
Tomato	*Lycopersicon Lycopersicum*	2.5	9.9	MS
Turnip	*Brassica Rapa*	0.9	9.0	MS
Watermelon	*Citrullus lanatus*	-	-	MS

[1]Percent reduction in yield per increase in solinity unit (ds/m).
[2]S, T, MS, and MT indicate a classification of sensitive, tolerant, moderately sensitive, and moderately tolerant, respectively.

Plant Factors

While plant species are classed as to their general sensitivity to salinity, considerable flexibility may be achieved by varietal selection, especially within the grass family (Gramineae). Rootstock differences in the tolerance of salinity and toxic ions are an important consideration for vine and fruit-tree crops. Several woody species show tolerance levels that are related to the accumulation properties of the rootstocks.

For some crops, salinity sensitivity varies with growth stage; cereal crops appear particularly variable. Rice, barley, wheat, and corn appear to be more sensitive during emergence and early seedling growth than at germination and later growth stages and grain development. Sugar beets and safflower are more sensitive during germination than at other stages.

Soil Factors

Immediately after an irrigation event the salt concentration of the soil solution will be at the lowest possible level. With ET, the solution becomes more concentrated as the time for the next irrigation approaches. As indicated previously, with very saline soil water, frequent irrigations are needed to minimize salinity stress; however, maintaining frequent irrigations may lead to aeration problems, especially for fine-textured soils.

Crops grown on infertile soils may exhibit quite high levels of apparent salt tolerance because salinity is not the factor limiting growth. Proper fertilization results in higher yield, but it seems to increase salt sensitivity.

Climatic Factors

Temperature, humidity, and air pollution have been observed to markedly influence salt tolerance. As evaporation demand increases (high temperature and lower relative humidity), many crops appear less salt tolerant. The detrimental effects of ozone have been observed to be moderated by maintaining moderate levels of salinity. This interaction may be of practical significance for some leafy vegetables and forage crops.

Specific Ion Effects

A few specific ions have a direct toxic effect on certain sensitive crops at relatively low concentrations. Tree crops and woody ornamentals are sensitive to low concentrations of sodium and chloride; annual crops do not show this degree of sensitivity. Boron affects a broad range of crop species. Studies of crop sensitivity to specific ions generally report absorption to be through the crop root system; an equally important mode of entry, in the case of sodium and chloride ions, is through leaves wet by a sprinkler.

Boron may be present in either soils or irrigation waters. In the soil, boron can be leached, but it is difficult to do so. Boron that is present in irrigation water requires corrective action by switching water supplies, if this is possible, or by selecting a crop less sensitive to boron. Table 1-9 provides a list of crops that have varying degrees of boron sensitivity.

Table 1-9.—*Tolerance classification of plants to boron (Robert S. Ayers, 1977. Quality of water for irrigation. J. Irrig. Drain. Div. ASCE, IR2, 103:135-154).*

Sensitive*	Semitolerant*	Tolerant*
Lemon	Lima beans	Carrot
Grapefruit	Sweet potato	Lettuce
Avocado	Bell pepper	Turnip
Orange	Tomato	Cabbage
Thornless blackberry	Pumpkin	Onion
Apricot	Zinnia	Broad bean
Peach	Oat	Gladiolus
Cherry	Milo	Alfalfa
Persimmon	Corn	Garden beet
Kadota fig	Wheat	Mangel
Grape (sultonina and malaga	Barley	Sugar beet
Apple	Olive	Palm (phoenix conariensis)
Pear	Ragged robin rose	Date palm (phoenix dactylifera)
American elm	Radish	Asparagas
Navy bean	Sweet pea	Athel (tamarix aphylla)
Jerusalem artichokes	Pima cotton	
Persian (English) walnut	Acola cotton	
Black walnut	Potato	
Peron	Sunflower (native)	

* Within each group, the plant first given is most sensitive and the last most tolerant.

Acid Soils

Soil leaching (weathering) takes place over much of the Earth's land surface where rainfall exceeds evapotranspiration for the greater part of the year. The leached soil becomes acidic as soluble salts, soluble soil minerals, and bases are removed. Under slight to moderate intensity weathering, only the surface soil becomes acidic while the subsoil may remain neutral or alkaline. As leaching becomes more intense, the entire soil profile becomes acidic. In humid tropical zones, strongly weathered soils return again to neutral to slightly acid conditions if soils are high in aluminum (Al) and iron (Fe) hydroxide.

Many factors other than the normal weathering processes of soils cause them to be acid. The parent materials of the soils may have been acidic, or the soils may have been contaminated by mine spoils containing iron pyrite (FeS_2) or other sulfides which are oxidized to H_2SO_4 and $Fe(OH)_3$ in the presence of air and water and can result in soils having a pH as low as 2. Marine flood plains that are high in sulfides become extremely acid in one to two years following drainage. Organic acids are formed as plant residues are decomposed by organisms and cause forest soils and organic soils to be acidic. Acid precipitation, having a pH as low as 3 to 4 because of the emissions from the combustion of fossil fuels (coal and petroleum), may lower the pH of sensitive soils, noncalcareous soils that have low organic matter contents and low clay contents and, consequently, very low cation-exchange capacities. Finally, most nitrogen and phosphorous fertilizers increase the acidity of soils. Nitrogen increases the acidity of soils when the ammonium form is converted to nitrate by soil micro-organisms; and diammonium phosphate does so when the ammonium ions, which are part of the chemical formula of the fertilizer, are also converted to nitrate.

Chemistry of Acid Soils

The chemical nature of acid soils is linked closely to the solution chemistry of Al and, to some extent, Fe. When the soil cation-exchange capacity is saturated with hydrogen ions from strong acids, the hydrogen ions are rapidly replaced with Al and Fe ions from within the crystal structure of the clay mineral.

Hydrolysis reactions lead to hydroxy complexes such as $Al(OH)^{2+}$, $Al(OH)_2^+$, and $Fe(OH)(H_2O)_5^{2+}$. Such reactions are important because these compounds form a thin layer around layered silicate minerals; and, because they are positively charged, they influence the cation-exchange capacity of soils. At low soil pH values (4.5 to 5.0), the net cation-exchange capacity of the soil will be lowest because the 2+ ion species above predominate and neutralize some of the negative charge. At neutral to slightly basic conditions, $Al(OH)_3^0$ is the dominant species and the net negative charge of the mineral complex is that of the silicate mineral. In highly weathered soils, oxides of Fe and Al are abundant. Such soils may have a large part of the cation-exchange capacity that is pH dependent.

Effects of Soil Acidity on Plant Growth

Many soil parameters are changed as soil acidity is altered; therefore, it is difficult to determine the exact reason for poor plant growth under acid conditions. Many experiments have emphasized, however, the different nutritional abnormalities that take place under field conditions. Provided the soil pH does not go below 4.0 - 4.5, there is little direct detriment because of hydrogen ions; rather, Al_3^+ and Mn_2^+ are present in soil solution in sufficient quantities to be toxic to plants in varying degrees, depending on the species and cultivar of the specific crop.

Deficiencies of calcium (Ca) frequently hinder crop growth under acid soil conditions, as do deficiencies of magnesium (Mg) and molybdenium (Mo). Generally, phosphorous (P) availability is suppressed in acid soils, but the resulting deficiencies frequently have been acccounted for by P immobilization in roots by the conduction elements of plants. In addition to the direct effects of acidity on the chemical status of inorganic elements, the impedance of the populations and the activities of micro-organisms that are responsible for transformations involving nitrogen (N), sulfur (S), and phosphorus (P) reduce the availability of these elements to crops.

Correcting acid soil conditions by liming has, in some instances, been associated with reduced availability of some inorganic ions. Therefore, care should be taken that adequate amounts of affected ions are made available by fertilization. Liming acid soil reduces the availability of exchangeable potassium (K). Boron (B) deficiency has been associated with liming in the southern region of the United States and zinc (Zn) deficiencies have been attributed to liming. Figure 1-29 illustrates nutrient availability in acid soils.

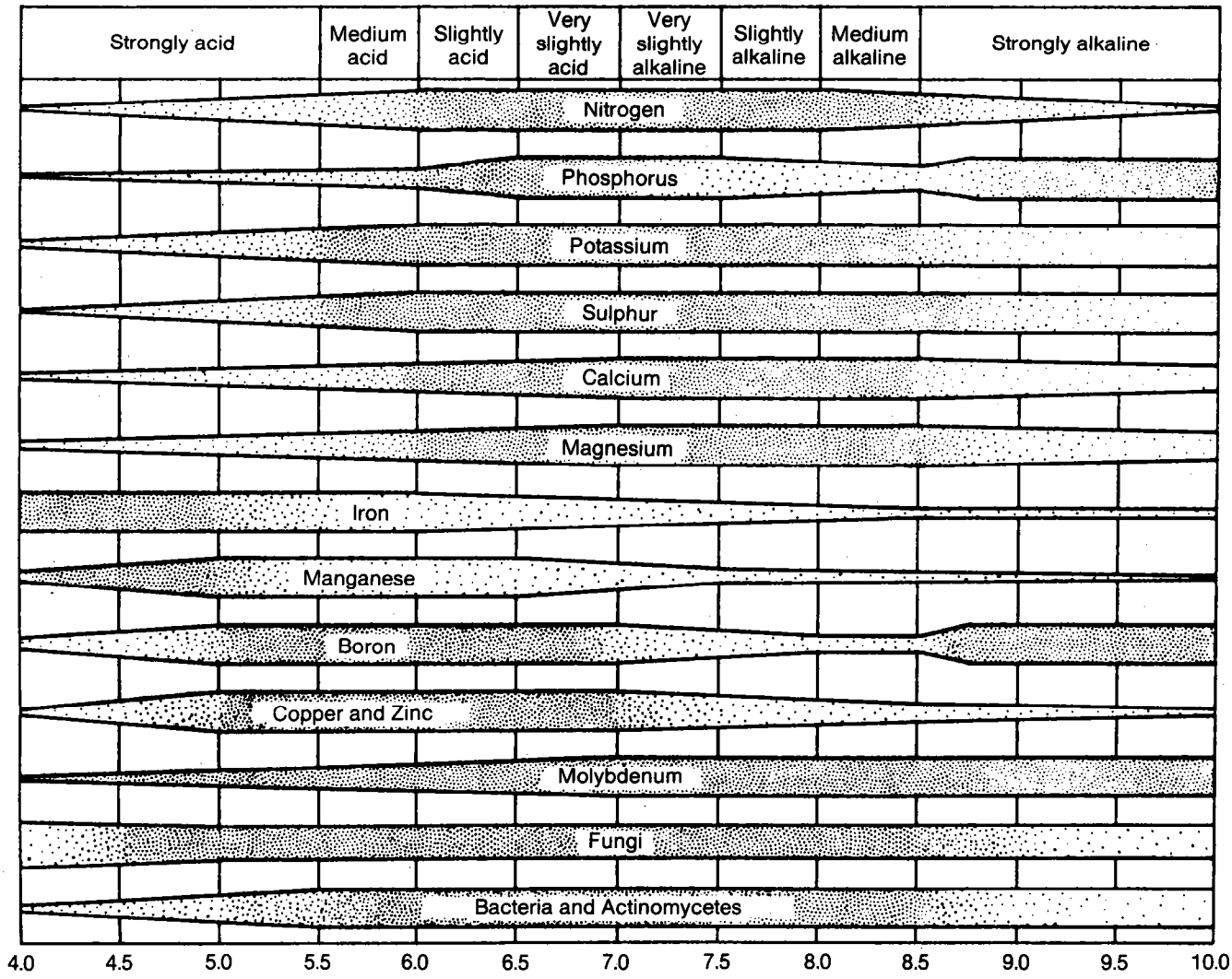
Crop Response to Liming in the United States

Soil acidity in the United States that is sufficient to limit crop production is generally restricted to subhumid and humid regions (fig. 1-1). Localized conditions that are favorable for acid soil development, however, may take place even in low rainfall areas.

Liming is considered to be an essential component of sustained crop productivity in the Southern United States. High usage of acid forming fertilizers increases the need for liming in the region; however, actual lime usage has not historically kept pace with that required for optimum crop production.

Figure 1-29.

Nutrient Availability in Acid Soils: The Wider the Bar, the More Available is the Nutrient.



Lime usage in the Midwest was higher before the 1950's when leguminous meadow crops were used extensively as a source of nitrogen to maintain acceptable crop yields. Following this period, the use of large quantities of commercial N-fertilizer materials was introduced, and the basic cation reserves were markedly lowered. Soils now require regular applications of lime to maintain productivity.

Most soils in the Northeastern States require regular applications of lime for normal plant growth and yield. Some very young limestone-derived soils are still calcareous in their upper horizons and require no lime at this stage of development. As in all regions, some growing crops actually perform best on acid soils.

In the Western States, precipitation that is sufficient to develop acid soil conditions in the normal course of soil development is restricted to areas relatively close to the Pacific Ocean. These areas are most frequently of mountainous terrain on the western slope that is not substantially cultivated.

Determining Lime Requirement

Contrasting crop species vary considerably in their tolerance of acid soils; therefore, the crops that are to be

grown affect liming recommendations. Table 1-10 gives the optimum soil pH range for several crops commonly grown on mineral soils in regions requiring lime additions. Some potato growers in Maine maintain low pH to control scab disease. Legumes are generally the crops most sensitive to soil acidity. Organic soils should be allowed to decline to much lower pH values than mineral soils; satisfactory crop yields are achieved at pH values ranging as low as 5.0 to 5.7. At these pH values organic soils usually contain an abundance of Ca and Mn. Generally, Al and Fe contents are well below toxic levels.

Table 1-10.—*Permissible soil pH ranges for various crops growing on mineral soils in Michigan (C. M. Woodruff, 1967.* In *Soil Acidity and Liming. Robert W. Pearson and Fred Adams, eds. Agronomy Monograph No. 12. Amer. Soc. Agron. Madison, WI, p. 222).*

Crop	Soil pH range	Crop	Soil pH range
Least acid-tolerant		More acid-tolerant	
Alfalfa	6.3 to 7.8	Buckwheat	5.0 to 7.0
Asparagas	6.0 to 8.0	Oats	5.0 to 7.0
Barley	6.5 to 7.8	Potatoes	5.2 to 6.5
Beans	6.0 to 7.5	Raspberry	5.0 to 7.0
Peas	6.0 to 7.5	Rye	5.0 to 7.0
Red clover	.0 to 7.5	Strawberries	5.0 to 6.5
Soybeans	6.0 to 7.0	Vetch	5.0 to 7.0
Sugar beets	6.0 to 7.5		
Sweet clover	6.5 to 7.9		
Medium acid-tolerant		Strongly acid soils required	
Corn	5.5 to 7.5		
Cotton	5.5 to 7.5	Cranberries	4.2 to 5.0
Grasses	5.5 to 7.5		
Trefoil	5.5 to 7.5		
Wheat	5.5 to 7.0		

A problem in managing acid soils is to determine the amount of lime needed to elevate soil pH to a desired level. Theoretically, the best procedure is to titrate a soil sample with a standard base to measure the amount of base needed to bring the pH to a specified level. To be accurate, however, a relatively long reaction time must accompany each titration step, which renders this approach somewhat impractical. A more commonly accepted technique is to add a pH buffer solution to the soil. The amount of buffer consumed or the pH of the soil-buffer suspension after equilibration is compared with the calibrated results of field lime experiments for similar soils of a specific geographic region.

The Ca and Mg compounds in agricultural lime will neutralize soil acidity. A listing of liming materials includes quicklime, hydrated lime, limestone, marl, shells, by-products such as slag, and irrigation water. The calcium and magnesium contents of ground water that is used for irrigation can be equal to 1,000 pounds or more of calcium carbonate per acre foot of water and can neutralize all the acidity generated by added fertilizers, yet still raise the pH of the soil over a period of time.

If the soils to be irrigated have a sodium adsorption ratio greater than 13 and the irrigation water contains calcium or magnesium and carbonate or bicarbonate ions, a slightly or moderately acid soil is preferable. In the acid soil calcium ions remain in the soil solution, rather than precipitating as the carbonate, and compete with sodium ions for adsorption on the exchange complex. The dispersion of clays due to sodium can also be reduced by maintaining some salinity in the irrigation water.

Limestone is the most common liming material used; it may be calcite ($CaCO_3$), dolomite ($CaCO_3 \cdot MgCO_3$), or a mixture of these materials. Agricultural lime usually contains impurities that have no effect on soil acidity. The chemical effectiveness of lime is measured by its $CaCO_3$ equivalency.

The rate of the reaction of lime with soil depends not only on its chemical purity, but also on particle size. Fineness is usually measured by expressing the percentages of material passing a series of specific, sized sieves. The approximate amounts of finely ground limestone that are needed to raise the pH of soils are shown in table 1-11. Adjustment of these amounts may be required to fit local conditions.

Table 1-11.—*Approximate amounts of finely ground limestone needed to raise the pH of a 7-inch layer of soil.*[1]

Soil regions and textural classes	Limestone requirements		
	From pH 3.5 to pH 4.5	From pH 4.5 to pH 5.5	From pH 5.5 to pH 6.5
Soils of warm-temperate and tropical regions:[2]	-------Tons per acre-------		
Sand and loamy sand	0.3	0.3	0.4
Sand loam	—	0.5	0.7
Loam	—	0.8	1.0
Silt loam	—	1.2	1.4
Clay loam	—	1.5	2.0
Muck	2.5[3]	3.3	3.8
Soils of cool-temperate and temperate regions:[4]			
Sand and loamy sand	0.4	0.5	0.6
Sandy loam	—	0.8	1.3
Loam	—	1.2	1.7
Silt loam	—	1.5	2.0
Clay loam	—	1.9	2.3
Muck	2.9[3]	3.8	4.3

[1]All limestone goes through a 2 mm mesh screen and at least 1/2 through a 0.15 mm mesh screen. With coarser materials, applications need to be greater. For burned lime, about 1/2 the amounts given are used; for hydrated lime, about 3/4.

[2]Red-yellow podzolic, red latosol, etc.

[3]The suggestions for muck soils are for those essentially free of sand and clay. For those containing much sand or clay the amounts should be reduced to values midway between those given for muck and the corresponding class of mineral soil. If the mineral soils are unusually low in organic matter, the recommendations should be reduced about 25 percent; if unusually high, increased by about 25 percent, or even more.

[4]Podsol, gray-podzolic, brown forest, brown podzolic, etc.

Water Balance

A water balance procedure states the appropriate time to irrigate and the amount of water to apply. The water balance procedure requires specific information in order to make the proper calculations.

Figure 1-30 illustrates the components of a field water balance. Both rainfall and irrigation water are stored in the soil; therefore, the effective plant root zone provides a reservoir for water storage. In order to determine effectively the capacity of the reservoir, information is required for the water retaining properties of the soils and the root development characteristics of the individual crops. A reliable estimate of the potential ET or ET_o is required along with the appropriate crop curve so that k_c values are known. With ET_o and K_c, estimates of ET_{crop} are determined from the relation: $ET_c = (ET_o)(K_c)$.

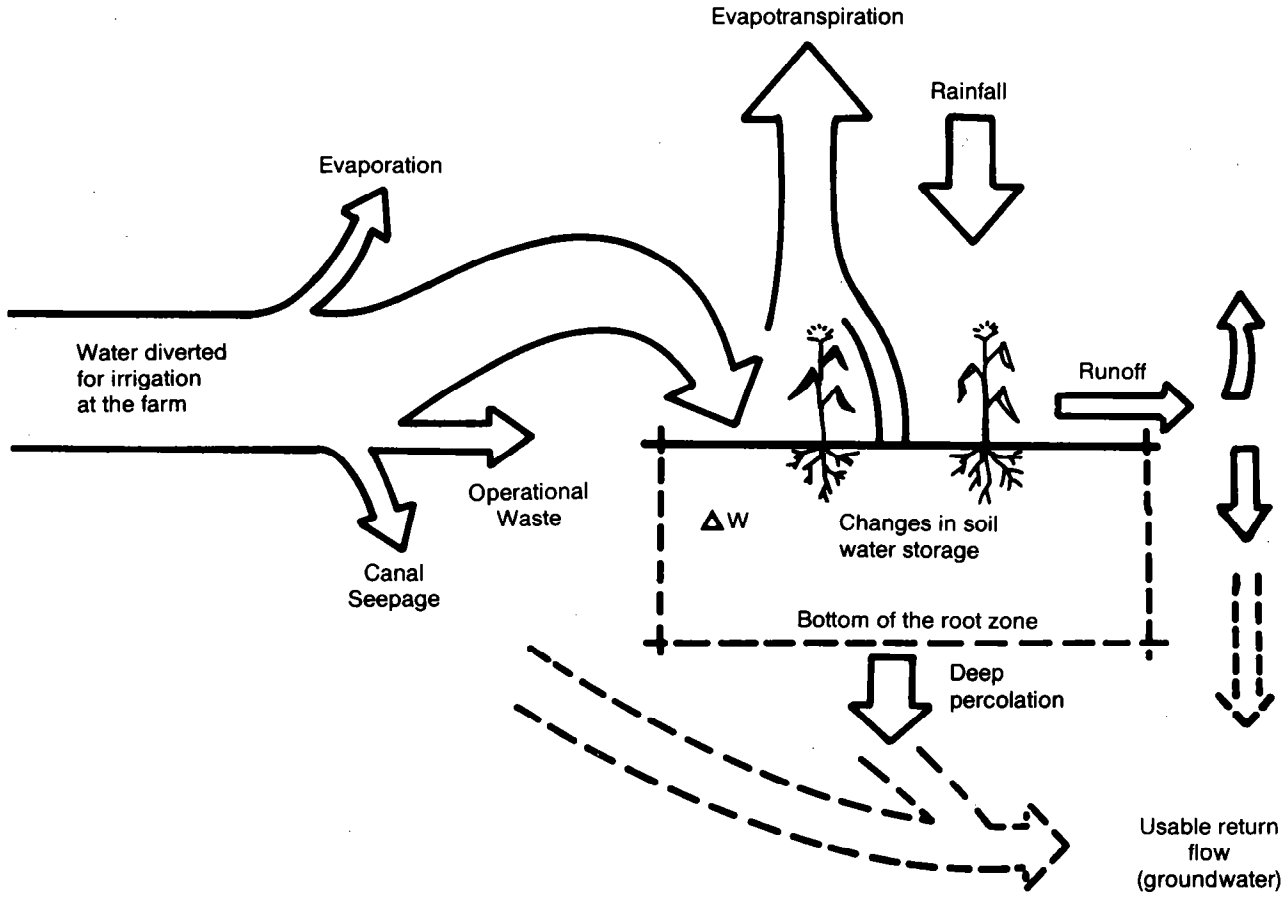
Allowable Water Depletion

Growth of most agricultural crops is favored by a soil water content that is high enough to encourage crop growth and development, but not so high that aeration becomes restrictive. These concepts are illustrated in figure 1-31. If soil water is plant-extracted to levels approaching the PWP, water is held so tenaciously by the soil that plants can no longer obtain sufficient water to meet the potential for transpiration. Transpiration is restricted and yield losses take place. Excessive filling of the soil pore space with water excludes sufficient air to meet plant oxygen requirements, and yields are again reduced. Plant species vary in their tolerance to either deficits or excesses. Water management programs must reflect individual crop characteristics.

A critical water level varies with the soil as well as with the crop. Figure 1-10 shows that at a 15 percent available water level the soil water tensions are at 5.8, 8.7, and 10.7

Figure 1-30.

Components of a Field Water Balance.



bars, respectively, for sand, loam, and clay. The water content of the sand, however, is almost down to the wilting point. More energy is required for a plant to extract water from the clay at the 15 percent level than from the sand at that level, but more water is available in the clay soil which provides a greater safety factor. To provide a reasonable safety factor, the lower limit of water depletion in the sandy soil must be higher than 15 percent for most crops. To illustrate this point, suppose the sand, loam, and clay soils hold 0.7, 1.4, and 2.4 inches of plant available water, respectively, per foot of soil depth at field capacity or 100 percent available water. At 15 percent available water remaining, there are 0.10, 0.21, and 0.36 inch per foot of soil depth for the sand, loam, and clay soils. For a root profile depth of five feet, the sandy soil only has a total of 0.5 inch of available water remaining.

Table 1-12 lists some commonly grown crops and suggested available water content that should remain in the soil profile at the time irrigations are made.

Table 1-12.—*Suggested percentage of available soil water content remaining in the crop root zone when an irrigation should be scheduled for several common crops.*

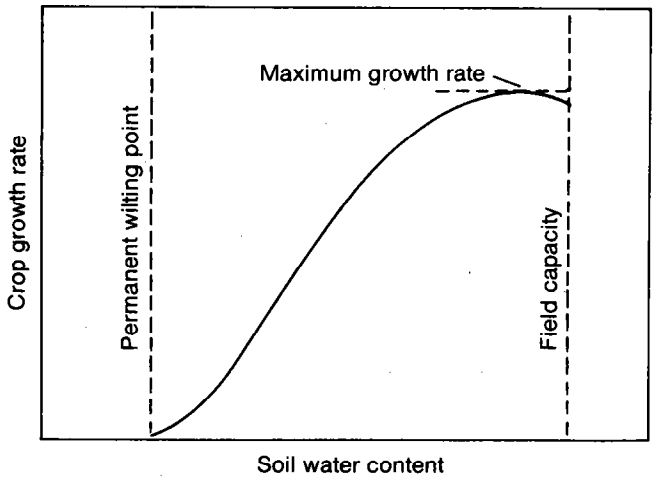
Crop	Season	First Irrigation	Later Irrigation
	percent of the available water remaining		
Potatoes	65	65	50 (vine killed)
Sugar beets	50	50	50
Sweet corn	60	40	60
Field corn	50	40	50
Mint	60	60	60
Beans	60	60	60
Small grains	40	40	60 (boot through flowering)
Onions	70	60	70
Alfalfa hay	50	50	50
Pasture	50	50	50

Soil-Water Extraction Depth

This is the soil depth used to determine the effective region of water uptake by plants. It is not necessarily the maximum rooting depth, especially for plants that have a long taproot. It is the depth to which an average mature plant can actively extract an appreciable amount of soil water. Because of the many factors that influence root development and proliferation, the effective depth must be determined for a specific location.

Figure 1-31.

Generalized Relationship Between Soil-Water Retention and Crop Growth



Net Water Calculations

The available water in a soil can be calculated if water contents representing FC and PWP are known for the appropriate soil depths. Some characteristics of a Hinckley loamy sand are given in table 1-13 to illustrate the procedure. The PWP is usually taken as the water content at the 15-bar tension level; FC is approximated by the 1/10 bar tension for sandy soils, and 1/3 bar represents the FC for medium- to fine-textured soils. For irrigation purposes, water content is expressed in units of water depth (inches, centimeters, etc.) per unit depth of soil; water and soil depths must be in the same units. Water content expressed in this manner represents a volumetric base instead of a gravimetric or weight base and is most appropriate for water depth calculations. Gravimetric water content is converted to a volumetric content by multiplying gravimetric water content by the soil bulk density. To calculate the available water between FC and PWP, the following formula can be used:

$$D = (B.\ D.)\ (d)\ (AWC)\ /\ (dw)\ (100)$$

where D is inches or centimeters of water in soil depth (d), B.D. is soil bulk density (grams oven dry soil/cm^3 volume sampled), d is soil depth in inches or centimeters, AWC is gravimetric water content between FC and PWP in percentage by weight, and dw is density of water taken as 1 g/cm^3.

Table 1-13.—*Water retention characteristics of a Hinckley loamy sand.*

Horizon	Textural class	Depth (in)	Bulk density (g/cm³)	1/10 bar[1] (gravimetric percent)	15 bar[2] (gravimetric percent)	In soil (in/in)	In horizon (in)
Ap	Loamy sand	0-8	1.15	21.1	8.3	0.147	1.18
B21	Loamy sand	8-14	1.25	22.5	8.7	0.172	1.03
B22	Loamy sand	14-20	1.23	17.0	5.1	0.146	0.88
C	Sand	20-26	1.39	9.8	3.0	0.095	0.57
D	Sand	26-32	1.47	6.0	1.4	0.068	0.41
						Total =	4.07

[1]Field capacity.
[2]Permanent wilting point.

The last two columns of table 1-13 were calculated using this formula. For example, the available water in the Ap horizon for a 1-inch soil depth is:

$$D = (1.15)\,(1)\,(12.8) / (1)\,(100) = 0.147 \text{ inch}$$

or (0.147 inch/inch) (8 inches) = 1.18 inches water for the Ap horizon.

For an irrigation system design, the total available water is calculated for a soil depth based on the root system of a mature plant of the crop to be grown. Root systems of plants were discussed earlier. The total amount of available water held by the soil of table 1-13 for all horizons is 4.07 inches. Suppose a mature, effective crop root system extends to a depth of 26 inches in this soil; then the total available water at FC in the root zone is 1.18 + 1.03 + 0.88 + 0.57 = 3.66 inches. If research or experience shows that crop yield is lowered when more than 50 percent of the available water is depleted from the effective or design root zone, then the crop should be irrigated when (0.50) (3.66) inches = 1.83 inches of water have been depleted from the soil profile.

Water Balance Accounting Procedures

The water-accounting procedure is based on two fundamental concepts, namely:

1. If there is an adequate supply of soil water, evapotranspiration rate for a given crop depends on the climatological evaporative demand.

2. If the soil water content of a soil is known at a given time, the water content at any later time can be computed by adding irrigation or rainfall and subtracting ET during the elapsed period.

Within recent years, reasonably reliable daily ET data have become available from climatic stations at strategic locations. This information is frequently available through one or more news media sources or computer linkage. By knowing the daily values at a site for rainfall events, ET, and net irrigation amount, the daily balance can be computed and compared to the amount of available water that can be depleted safely before an irrigation is required.

Computation is started when the soil is at field capacity or a known water content. Following a heavy rain or an irrigation, the soil may be at field capacity, but this should be verified in the field. The soil water content should always be verified at the starting time. At a given time of the day, each morning if convenient, the available water in the soil is computed by subtracting the previous day's ET from the previous morning's balance. The previous day's irrigation or rainfall is added to the previous morning's balance. When the daily balance reaches the point at which soil water is depleted to the predetermined allowable limit, it is time to irrigate. Ignoring application efficiency, the net amount of water to be replaced in the soil by irrigation is the amount that brings the soil water content up to FC. To arrive at the balance on the morning following irrigation, this amount is added. The balance is then computed daily until another irrigation is indicated. Should an irrigation amount not be adequate to return the profile to field capacity, the profile available water content is set to the actual amount present. This tactic is used in humid areas to more efficiently utilize rainfall should it occur shortly after an irrigation application and to reduce the leaching of nutrients into the ground water.

The water retention properties of table 1-13 can be used to illustrate the procedure. Suppose a crop rooting depth is 26 inches, the total plant available water is 3.66 inches for this depth in the Hinckley loamy sand. If a crop is allowed to deplete 60 percent of the amount, 2.2 inches of allowable depletion can occur before soil water must be replenished. A water balance accounting procedure for these conditions is shown in table 1-14.

When rainfall or irrigation takes place in excess of the amount needed to bring the soil back to FC, the extra amount is assumed to percolate below the root zone; the daily balance is recorded as the FC level. Should high intensity rains cause runoff before the soil is filled to FC, it will be necessary to either estimate or measure the effective rainfall percolating into the soil that is available for plant use. This amount is added to achieve the daily balance.

Table 1-14.—*Example of water balance accounting procedure.*

Day after initialing	Profile available water remaining (in)	ET of crop (in)	Cumulative ET (in)
0	3.66		
1	3.51	0.15	0.15
2	3.33	0.18	0.33
3	3.19	0.14	0.47
4	3.02	0.17	0.64
5	2.83	0.19	0.83
6	2.63	0.20	1.03
7	2.42	0.21	1.24
8	2.20	0.22	1.46
9	2.00	0.20	1.66
10	1.82	0.18	1.84
11	1.63	0.19	2.03
12	1.46	0.17	2.20

At the end of 12 days, 2.2 inches of water are needed to bring the profile back to field capacity.

Plant-Based Concepts

The primary advantage of plant-based measurements for irrigation scheduling is due to the fact that plant growth is directly related to plant water status and only indirectly related to soil water and atmospheric conditions. The plant essentially integrates its soil water and atmospheric environments and reflects the prevailing conditions in growth processes. Because the rate of many of these expansive growth processes are related to plant-water status, measurement of the plant-water status can yield valuable data indicative of plant growth and development.

The visual appearance of crops has been used for many years as a guide to scheduling irrigations. In the early 1960's, the pressure chamber became commercially available as a practical method for measuring leaf water potential. More recently, infrared thermometry techniques have been developed to measure leaf or canopy temperatures. Growing indicator plants that will exhibit water stress symptoms earlier than the crop itself is an old idea that is not used frequently. All plant-based techniques have in common the property of indicating when to irrigate, but they provide no information on how much water to add at an irrigation. Leaf water potential measurements and leaf or canopy temperature measurements provide excellent scheduling techniques; a good water management scheme can be achieved by combining these techniques with measurements of the soil water status in order to determine the required amount of irrigation water.

Pressure Chamber

The primary features of the pressure chamber are the chamber, pressure gauge, control valve, and a small nitrogen gas tank to serve as a pressure source. Leaving sufficient petiole length to extend through a sealed stopper to make a measurement, the petiole and attached leaf are cut from the plant. Once the petiole or spur is severed, water withdraws within the xylem vessels, because the external pressure is several times that inside the conducting tissue. Leaves are sealed inside the chamber with the petiole cut surface extending upward through a pressure-sealed rubber stopper or "O" ring. The chamber is pressurized to force the water in the xylem back exactly to the cut petiole surface; pressurization is stopped and a reading is taken from the gauge. The positive chamber pressure now matches the negative potential of the xylem fluid. Care must be taken during this measurement process to suppress water evaporation from the leaf so as to ensure accurate readings.

Pressure chamber readings change drastically during the day. Figure 1-32 shows two curves for different stress levels in cotton. Leaves have the highest leaf water potential just before sunrise. After sunrise the increased light causes stomata to open and transpiration begins; leaf water potential declines until approximately solar noon. Readings remain relatively stable after solar noon for about 2.5 to 3 hours; then leaf water potential progressively increases, reflecting plant water recovery until a slightly lower leaf water potential than the level of the previous day is reached in late evening or early morning.

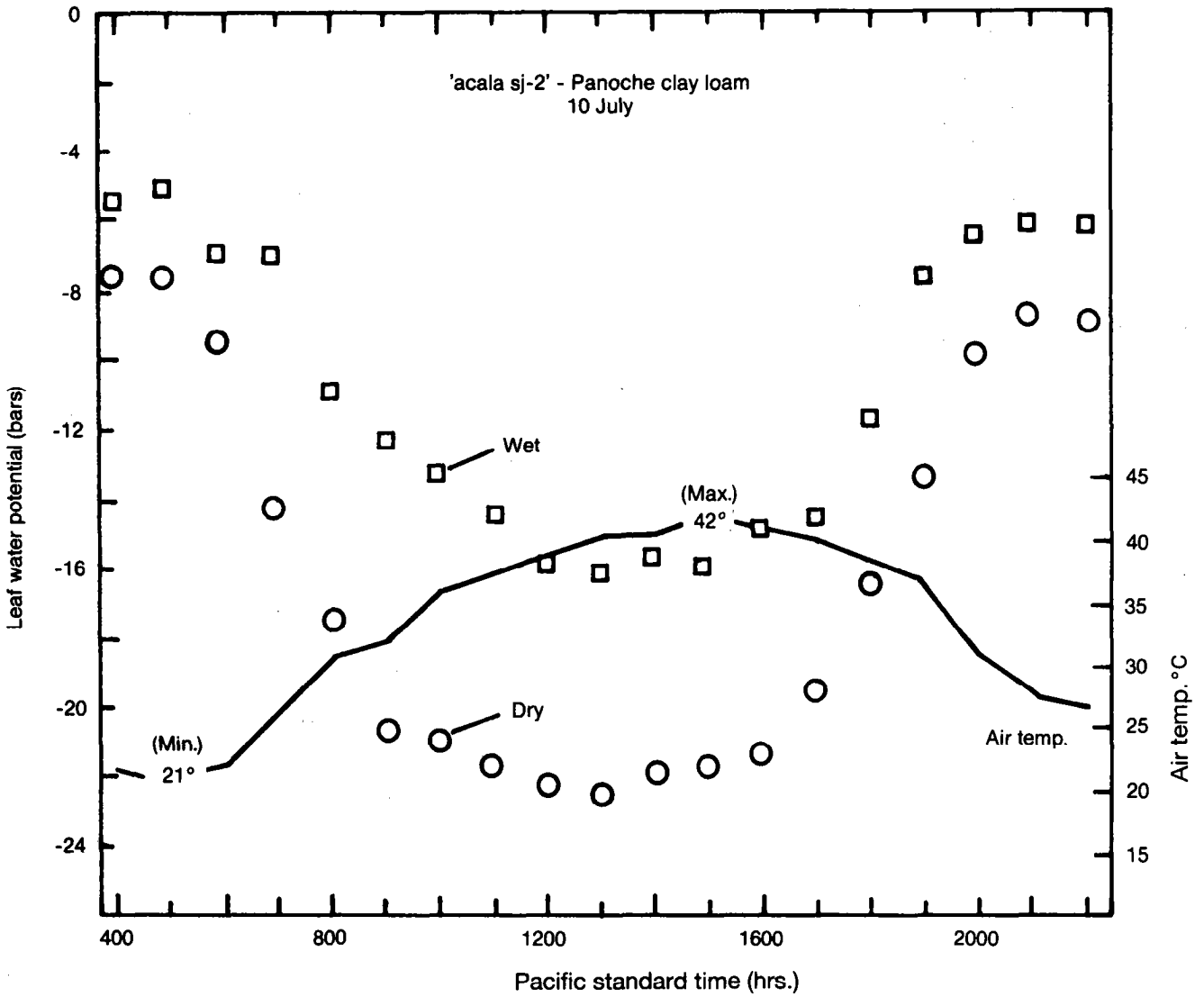
With cotton and some other crops, midday readings can be made conveniently for irrigation scheduling; however, some crops, like tomatoes, may have rather erratic midday readings due to stomatal closure when water stress develops. When this takes place, predawn readings of crop water status must be used to schedule irrigations. Predawn readings can be made on essentially all crop species.

Predawn leaf water potential uses the plant much like a tensiometer except the range of readings is not restricted to one atmosphere or less as with tensiometers. Readings reflect the integration of the soil matrix potential throughout the root zone. Research has shown that the relationship between soil water depletion and leaf water potential is linear. When correlated, the leaf water potential can be used to determine when to irrigate and how much water to apply.

There are some advantages, however, to making midday readings for those crops that allow this approach. At midday, greater differences in leaf water potential exist between water-stressed and adequately irrigated plants; this is illustrated for cotton in figure 1-32. An additional advantage is the convenience of making measurements at midday rather than predawn. Regardless of whether measurements are

Figure 1-32.

Diurnal Leaf Water Potential Curves for Cotton of Contrasting Water Stress Levels



made at predawn or at midday, success depends on having water status-growth relationships identified for individual crops. This information is available only for a few crop species, but research to develop more information is ongoing.

After an irrigation, pressure chamber readings decline linearly with time. The decline is fairly rapid for sandy soils that hold comparatively little available water for plants, but quite slow for clay soils that have a high water retention capability. Once the rate of decline has been established, the time to the next needed irrigation can be estimated by extrapolating the decline function. For uniform climatic conditions this estimate will be fairly accurate, but accuracy will decline with increased variability in evaporative demand.

Leaf or Canopy Temperature Methods

Crop leaf or canopy temperature measurements as a means of assessing crop water stress have been extensively researched in recent years, and the technique is proving to be

of considerable utility. The technique relies on the concept that, if a crop is well supplied with water, transpiration will be at the maximum possible rate and the crop canopy will be relatively cool compared to the surrounding air. When the available soil moisture is depleted to some threshold level, which depends on the environmental evaporation demand, transpiration will be reduced from the maximum potential and the crop canopy will increase in temperature. At this stage or later, photosynthesis is reduced; this results in yield reduction.

In using plant temperature measurements to quantify crop water stress, the foliage-air temperature difference is obtained. Because this parameter is influenced by environmental factors such as air vapor pressure deficit, net radiation, and windspeed in addition to soil water content, the leaf or canopy air temperature difference (T_f - T_a) is "normalized" for environmental variability. In this use, the term normalize means that the readings for crop stress will be constant regardless of whether the evaporative demand of a measurement time of day is high or low. The approach that is illustrated in figure 1-33 uses the air vapor pressure deficit alone to normalize the air (T_f - T_a) parameter. Since evaporative demand is normalized, readings can theoretically be made during a relatively broad time span; in practice, readings are usually done shortly after solar noon.

The two essential components of this method are a no water-stress base line for a particular crop and an upper limit representing T_f - T_a when transpiration is completely suppressed. A detailed discussion of the various parameters of the method is given by Idso et al.

A crop water stress index (CWSI) is calculated by measuring the relative amount of departure of T_f - T_a from the nonstressed base at a particular, observed value of vapor pressure deficit. A CWSI value of 0 represents no stress, and a value of 1 represents a total cessation of transpiration. As the rates of actual to potential evapotranspiration go from 1 to 0, the CWSI index goes from 0 to 1.

A considerable amount of reliable equipment is available commercially for making CWSI measurements. Advantages of this technique include the ability to make rapid measurements of a large number of plants, especially if canopy temperature is the measurement objective.

CWSI can be correlated with soil water depletion at a specific site. Information to date indicates that this relationship is linear until soil water is depleted to a relatively low level. When this is done, the CWSI can be used to determine when to irrigate and how much water to apply. Correlation of CWSI and soil water depletion can be made by periodically measuring the soil water content in the crop root zone and plotting CWSI vs. soil water depletion or by observing the change in CWSI when a specific amount of water is applied. The amount applied should be just enough to produce the return of the CWSI to the nonstressed condition.

Visual Appearance

The appearance of a crop gives some indication of when an irrigation is needed. Plant wilting is perhaps the most obvious sign of water stress; however, the growth of most crops may be retarded before visible wilting takes place.

Some crops undergo a distinct color change in the foliage with the onset of plant water stress. Beans, cotton, and peanuts, for example, become bluish green to dark green as available soil water becomes limiting. Color changes may be visible in such crops sufficiently early to allow irrigation without much yield loss.

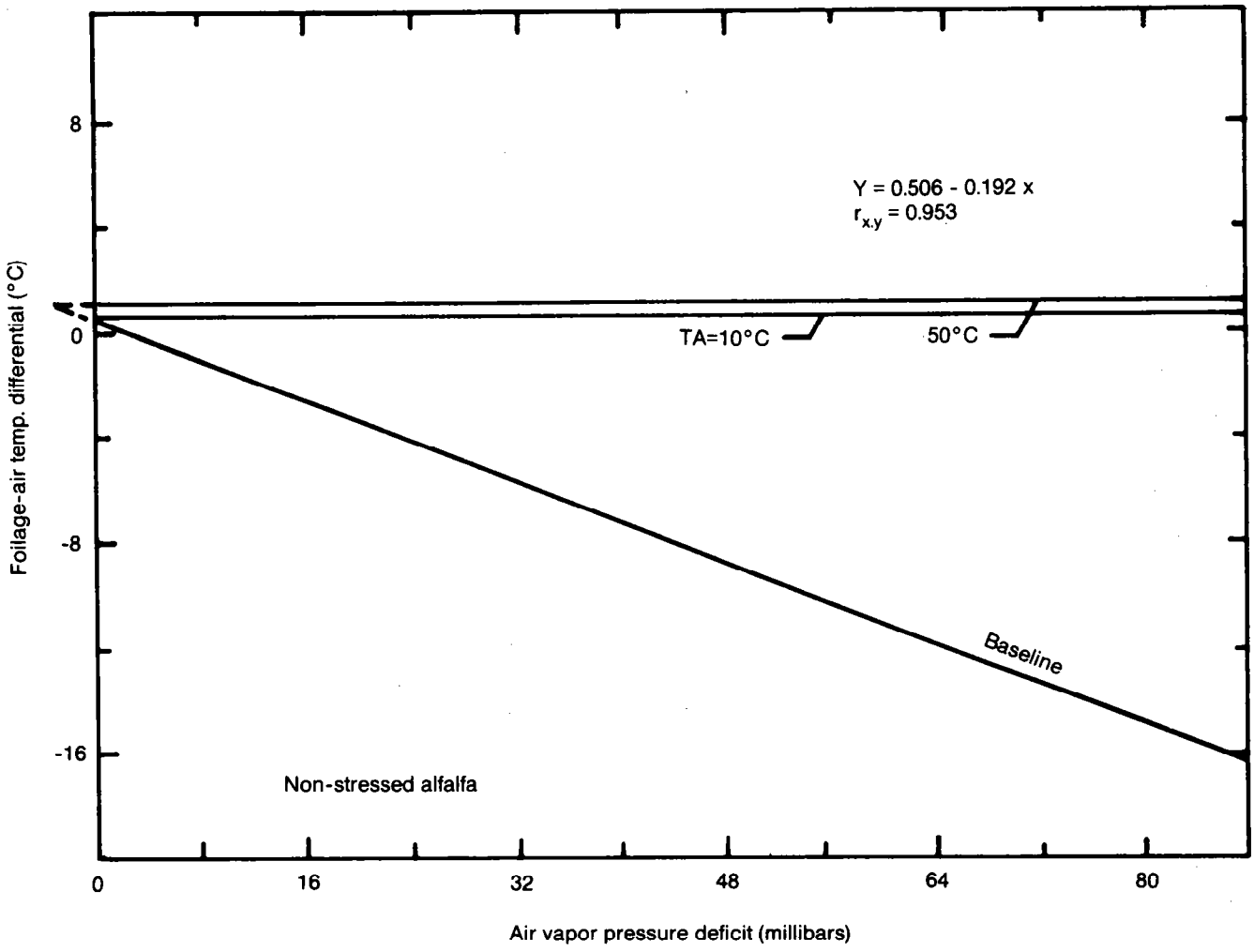
Pronounced diurnal movement of leaves takes place in some crops because of the reduced turgor pressure of plant cells. Sorghum undergoes changes in leaf angle that reportedly can be used successfully to schedule irrigation.

Indicator Plants

Indicator plants that are naturally more susceptible to soil water deficits can be used to provide a visual signal for a needed irrigation. A general requirement is that the indicator plant must have a top to root ratio exceeding the main crop; therefore, water stress will occur earlier for the indicator plants. The crop itself can be used this way by preparing test plants that have restricted root systems. Restricted root systems can be achieved by mechanical barriers or by placement of the plants in a soil that is mixed with sand to reduce its available water supply.

Figure 1-33.

Foliage-Air Temperature Differential Versus Air Vapor Pressure Deficit for Well-Watered Alfalfa Grown at a Variety of Specific Sites and Dates



Automation in Irrigation Scheduling

Plant water uptake to satisfy growth and evapotranspiration processes follows a diurnal cycle. The water moves from a periodically replenished root zone (source), through the plant, then to the atmosphere (sink). At the end of a typical irrigation cycle, soil-water storage becomes depleted, the hydraulic conductivity decreases drastically, and the root system cannot resupply water fast enough to meet the atmospheric evapotranspiration demand of the plant, thereby creating a plant-water deficit or stress condition.

Irrigation methods capable of operating frequently, such as mini-sprinkler, trickle, and subsurface, offer the means to maintain soil water at nearly constant levels. They place the soil-water-root environment under the control of the irrigator, whether the irrigator is a human or computer. Because any disruption to the irrigation schedule creates detrimental water or oxygen stress for the crop automatically, control of high-frequency irrigation must be automatic, redundant, and capable of responding to small and rapid changes in soil water, plant water, or evapotranspiration.

Scheduling frequent irrigations can be accomplished with automatic feedback control that is based on soil water potential. Because the storage capacity of soil is deemphasized and water is applied to supply the water potential continuum and match the evapotranspiration rate, there is less margin for error. Timeliness is important.

To monitor soil moisture and control an irrigation system automatically, equipment is required that will sample several sensors sequentially, will compare each sensor output to the set threshold level, and will compute outputs capable of controlling the irrigation system. Desktop computers and microprocessors have been used successfully.

In addition, commercial equipment is available to measure soil matric potential and to control the irrigation system automatically. The computer calculates the average readings of soil matric potential sensors, compares the average soil matric potential that is measured to the threshold value at which each irrigation is to be applied, and turns on the irrigation system for a preselected time period if needed.

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Part 623
National
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Chapter 2 Irrigation Water Requirements

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Preface

Irrigation is vital to produce acceptable quality and yield of crops on arid climate croplands. Supplemental irrigation is also vital to produce acceptable quality and yield of crops on croplands in semi-arid and subhumid climates during seasonal droughty periods. The complete management of irrigation water by the user is a necessary activity in our existence as a society. Competition for a limited water supply for other uses by the public require the irrigation water user to provide much closer control than ever before. The importance of irrigated crops is extremely vital to the public's subsistence.

Todays management of irrigation water requires using the best estimate that current technology can provide for the determination of crop water use and field irrigation water requirements. Support for many of the estimated values included in this chapter come from field research and many field evaluations over many years. Field evaluations and ground truthing must always be used to further refine the estimates used for planning irrigation systems. This chapter of the SCS National Engineering Handbook (NEH) provides that current technology. It provides nationwide acceptable procedures to determine crop water needs. The specific procedure or equation used depends on the availability of specific climatic data needed for that process and the desirable intensity level of managing irrigation water.

Chapter 2 describes the processes that affect water use requirements for a crop, field, farm, group of farms, or project level evaluation. The processes include evaluation of crop water use, climatic relationship and data, reference crop evapotranspiration, crop coefficients, leaching requirements for salinity control, temperature control and other auxiliary water requirements, effective precipitation, water table contribution, irrigation efficiencies, on-farm irrigation requirements, and project irrigation requirements. This chapter provides the processes for determining irrigation water requirements for state and local irrigation guides.

Chapter 2 of Part 623 is a new chapter to the family of chapters currently in NEH Section 15, Irrigation. It is written for employees of the Soil Conservation Service who provide technical assistance to the water user with concerns for both water quantity and water quality. Other technical personnel from Federal, State, private, and local agencies will also find the chapter very useful as a basic reference when providing technical assistance relating to irrigation water requirements.

Other chapters in NEH section 15 describe

- Soil-plant relationships and soil water properties that affect movement, retention, and release of water in soil
- Planning farm irrigation systems
- Measurement of irrigation water
- Design of pumping plants
- Design criteria and design procedures for surface, sprinkler, and micro irrigation methods and the variety of systems for each method that can be adaptable to meet local crop, water, and site conditions and irrigation concerns

These chapters will come under the new Part 623, Irrigation, in the National Engineering Handbook series.

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Chapter 2 Irrigation Water Requirements

Contents:

623.0200 Water requirements 2–1
(a) Introduction 2–1
(b) Irrigation requirements 2–1

623.0201 Crop water use 2–4
(a) Introduction 2–4
(b) Evapotranspiration processes 2–4
(c) Direct measurement of evapotranspiration 2–8
(d) Estimating crop evapotranspiration 2–11

623.0202 Climatic relationships and data 2–13
(a) Introduction 2–13
(b) Barometric pressure 2–13
(c) Air properties 2–14
(d) Wind relationships 2–18
(e) Estimating net radiation 2–22
(f) Estimating solar radiation 2–32
(g) Soil heat flux 2–34
(h) Weather stations 2–37

623.0203 Reference crop evapotranspiration 2–41
(a) Selection and application of reference crop ET method 2–41
(b) Penman-Monteith method 2–43
(c) Radiation method 2–52
(d) Temperature method 2–56
(e) Evaporation pan method 2–62
(f) Summary 2–65

623.0204 Crop coefficients 2–66
(a) Fundamental concepts 2–66
(b) Determining basal crop coefficients 2–69
(c) Water stress factor 2–82
(d) Wet soil evaporation 2–85
(e) Average crop coefficients 2–88
(f) Estimating evaporation during the nongrowing season 2–91
(g) Adjusting crop coefficients for real-time predictions 2–92
(h) Sensing ground cover 2–97
(i) Summary 2–97

623.0205 Leaching requirements for salinity control 2–98
(a) Significance of salinity 2–98
(b) Water quality evaluation 2–99
(c) Crop salt tolerance 2–104
(d) Leaching for salinity control 2–115
(e) Salinity management alternatives 2–125
(f) Reclamation of salt-affected soils 2–129

623.0206 Auxiliary irrigation water requirements 2–133
(a) Frost protection 2–133
(b) Crop and soil cooling 2–137
(c) Wind erosion control 2–138
(d) Chemigation 2–139
(e) Plant disease control 2–140
(f) Seed germination 2–141

623.0207 Effective precipitation 2–142
(a) Introduction 2–142
(b) Definition of effective precipitation 2–142
(c) Processes controlling effective precipitation 2–142
(d) Factors affecting effective precipitation 2–144
(e) Estimating effective precipitation 2–146
(f) Carryover soil moisture 2–154

623.0208 Water table contribution 2–155
(a) Introduction 2–155
(b) Steady upward flow 2–158
(c) Hydraulic properties of soil 2–162

623.0209 Irrigation efficiencies 2–164
(a) Introduction 2–164
(b) Irrigation efficiency (E_i) 2–164
(c) Uniformity of application 2–167
(d) Application efficiency (E_a) 2–168
(e) Irrigation adequacy 2–170
(f) Conveyance efficiency (E_c) 2–181

623.0210 Onfarm irrigation requirements 2–187
(a) Net seasonal irrigation requirements 2–187
(b) System capacity requirements 2–194
(c) Net system capacity 2–197
(d) Irrigation scheduling 2–209

623.0211 Project water requirements **2–216**
(a) Introduction 2–216
(b) Irrigation project requirements 2–216
(c) Onfarm delivery schedules 2–223
(d) Water conservation 2–225

Appendix A Blaney-Criddle Formula (SCS TR–21) **2–227**

Appendix B Day of Year Calendar **2–259**

References **2–261**

Glossary **2–267**

Symbols **2–275**

Index **2–281**

Tables

Table 2–1 Locations of procedures to estimate irrigation water requirements 2–3

Table 2–2 Albedo for natural surfaces 2–6

Table 2–3 Average daily value of climatic parameters for an example site near Dodge City, Kansas 2–13

Table 2–4 Ratio of wind speeds based on measurement heights 2–19

Table 2–5 Daytime wind speed 2–21

Table 2–6 Clear sky radiation at sea level for various latitudes and dates 2–26

Table 2–7 Clear sky radiation correction term for elevation 2–27

Table 2–8 Values of the a_1 parameter and the atmospheric emittance 2–30

Table 2–9 Emittance of longwave radiation by a perfect black body 2–31

Table 2–10 Extraterrestrial radiation 2–33

Table 2–11	Selected air properties for varying temperatures and elevations	2–45
Table 2–12	Aerodynamic resistancefor various wind speeds and common configurations of weather stations	2–47
Table 2–13	Adjustment factor b_r for the radiation method	2–54
Table 2–14	Value of parameters used with the radiation method	2–55
Table 2–15	Values of adjustment factor a_t for use in equation 2–50	2–58
Table 2–16	Values of adjustment factor b_n for use in equation 2–51	2–59
Table 2–17	Values of adjustment factor b_u for use in equation 2–51	2–60
Table 2–18	Daily percent of annual daytime hours	2–61
Table 2–19	Pan coefficients for Class A evaporation pans for different ground cover and levels of mean relative humidity and 24-hour wind run	2–63
Table 2–20	Basal crop coefficient parameters for field and vegetable crops for a grass reference crop	2–73
Table 2–21	Basal crop coefficients for alfalfa, clover, grass-legumes, and pastures using a grass reference crop	2–77
Table 2–22	Basal crop coefficients for citrus grown in predominantly dry areas with moderate wind using a grass reference crop	2–78
Table 2–23	Basal crop coefficient for full grown deciduous fruit and nut trees using a grass reference crop	2–79
Table 2–24	Basal crop coefficients for sugarcane using a grass reference crop	2–80
Table 2–25	Basal crop coefficients for grapes with clean cultivation, infrequent irrigation, and dry soil surface most of the season using a grass reference crop	2–80
Table 2–26	Crop coefficients for paddy rice grown in the United States mainland using a grass reference crop	2–81
Table 2–27	Monthly crop coefficients for some perennial crops raised in Northwestern United States	2–81

Table 2–28	Fraction of the soil surface wetted for various types of irrigation	2–85
Table 2–29	Wet soil surface evaporation decay function f(t) and the persistence factor P_f for typical soils	2–86
Table 2–30	Average wet soil evaporation factor	2–88
Table 2–31	Hanway's stages of growth for corn	2–93
Table 2–32	Irrigation water quality guidelines	2–100
Table 2–33	Determinations normally required to evaluate irrigation water quality problems	2–101
Table 2–34	Salt tolerance of selected crops	2–106
Table 2–35	Chloride tolerance limits of some fruit crop cultivars and rootstocks	2–111
Table 2–36	Relative tolerance of selected crops to foliar injury from saline water applied by sprinklers	2–112
Table 2–37	Boron tolerance limits for agricultural crops	2–113
Table 2–38	Citrus and stone fruit rootstocks ranked in order of increasing boron accumulation and transport to leaves	2–114
Table 2–39	Estimates of the electrical conductivity of drainage water for determination of the leaching requirements	2–116
Table 2–40	Sprinkling rate necessary for frost protection	2–135
Table 2–41	Temperatures to start and stop overtree frost protection	2–135
Table 2–42	Factors influencing effective precipitation	2–144
Table 2–43	Average monthly effective precipitation as related to mean monthly precipitation and average monthly crop evapotranspiration	2–148
Table 2–44	Sample calculation of effective precipitation (corn at Raleigh, North Carolina)	2–152
Table 2–45	Sample calculation of effective precipitation (alfalfa at Denver, Colorado)	2–152

Table 2–46	Average ratios applicable to effective precipitation	2–153
Table 2–47	Average values for parameters used in the Brooks and Corey functions	2–163
Table 2–48	Probable application efficiencies of the low-quarter and the low-half for various types of sprinkler systems	2–173
Table 2–49	Example water application efficienciesfor furrow irrigation by slope and intake family assuming no reuse of runoff	2–175
Table 2–50	Example water application efficiencies for furrow irrigation by slope and intake family assuming a runoff reuse efficiency of 75 percent	2–176
Table 2–51	Suggested application efficiency for graded border irrigation systems	2–179
Table 2–52	Design application efficiency of level systems as function of the advance ratio AR, where AR = advance time/net opportunity time = T_t/T_n	2–180
Table 2–53	Conveyance, field, and distribution efficiencies for various types of systems	2–185
Table 2–54	Average 5-day ET_c data for the log-normal frequency analysis data	2–202
Table 2–55	Peak period average daily consumptive use as related to estimated actual monthly use	2–205
Table 2–56	Comparison of the effect of an earliest date and latest date irrigation strategy on system capacity and other performance criteria	2–208
Table 2–57	Example of canal sizing problem for the system shown in figure 2–65	2–224
Table 2A–1	Monthly percentage of daytime hours of the year for northern latitudes	2–228
Table 2A–2	Seasonal consumptive-use crop coefficients for irrigated crops	2–230

Table 2A–3	A guide for determining planting dates, maturity dates, and lengths of growing seasons as related to mean air temperature	2–231
Table 2A–4	Values of the climate coefficients for various mean air temperatures	2–232

Figures

Figure 2–1	Diagram of the soil-water balance of a crop root zone	2–2
Figure 2–2	Flow chart to compute irrigation water requirements	2–3
Figure 2–3	Energy available for evapotranspiration from crop systems	2–5
Figure 2–4	Schematic diagram of three types of lysimeters used to measure crop evapotranspiration	2–9
Figure 2–5	Relationship of vapor pressure and relative humidity to temperature	2–14
Figure 2–6	Representation of wind speeds within and above a crop canopy	2–18
Figure 2–7	Variation of albedo during the year for selected latitudes	2–23
Figure 2–8	Effect of date and elevation on clear sky radiation at 40°N latitude	2–24
Figure 2–9	Extraterrestrial radiation as a function of time for various latitudes	2–32
Figure 2–10	Flow chart for computing net radiation	2–35
Figure 2–11	Changes in ET_o with distance from the ocean for three locations in California	2–38
Figure 2–12	Effect of advection on the evaporation rate from an evaporation pan	2–39
Figure 2–13	Correction factor for evapotranspiration because of advection using data outside or before irrigation development for different sizes of irrigated areas under arid and moderate wind conditions	2–40

Figure 2–14	Variation of the average daily ET_c as affected by the length of the averaging period	2–42
Figure 2–15	Definition sketch for variables used to define the aerodynamic resistance	2–44
Figure 2–16	Flow diagram for computing ET_o using the Penman-Monteith method	2–49
Figure 2–17	Schematic diagram of a Class A evaporation pan	2–62
Figure 2–18	Plot of pan evaporation against Penman-Monteith ET_o to determine a pan coefficient	2–64
Figure 2–19	Generalized basal crop coefficient showing the effects of surface wetness, water stress, and leaf area index during the growing season	2–67
Figure 2–20	Basal crop coefficient for corn grown for grain in a windy and arid environment	2–70
Figure 2–21	Process to compute basal crop coefficients	2–72
Figure 2–22	Functions used to reduce evapotranspiration based on soil-water content	2–83
Figure 2–23	Comparison of basal and average crop coefficients for the average crop coefficient example	2–90
Figure 2–24	Example of the relationship of growth stages of corn to cumulative growing degree days since emergence for western Nebraska	2–93
Figure 2–25	Example of the relationship of crop development to growing degree days for Pioneer 3901 corn grown for 5 years in western Nebraska and 2 years in eastern Nebraska	2–94
Figure 2–26	Variation of growing degree days required from emergence to maturity for six corn varieties of different maturity ratings	2–95
Figure 2–27	Crop growth stages for corn related to the fraction of the growing season based on growing degree days	2–95
Figure 2–28	Example soil-water retention curves for a clay loam soil at various degrees of soil salinity	2–99

Figure 2–29	Relationship among average root zone salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of conventional irrigation management	2–102
Figure 2–30	Relationship among water uptake-weighted salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of high-frequency irrigation	2–102
Figure 2–31	Threshold values of Sodium Adsorption Ratio of topsoil and electrical conductivity of infiltrating water associated with the likelihood of substantial losses in permeability	2–103
Figure 2–32	Divisions for classifying crop tolerance to salinity	2–105
Figure 2–33	Prediction of leaching requirement based on crop tolerance and water salinity	2–117
Figure 2–34	Evaporation from land areas for various temperatures and rates of rainfall	2–120
Figure 2–35	Pattern of salt buildup as a function of bed shape and those effects on the germination of seeds placed at different locations on the beds	2–127
Figure 2–36	Depth of water per unit depth of soil required to leach a saline soil by continuous or intermittent ponding, or to leach a soil inherently high in boron	2–130
Figure 2–37	Precipitation pathways	2–143
Figure 2–38	Average monthly effective precipitation as related to mean monthly rainfall and average crop evapotranspiration	2–149
Figure 2–39	Frequency distribution of growing season precipitation	2–151
Figure 2–40	Hydraulic properties for sand and silt loam	2–156
Figure 2–41	Water content and capillary pressure head for two soils that have a steady, upward flow rate of 0.1 inch per day	2–157
Figure 2–42	Water table contribution to irrigation requirements as a function of water table depth	2–159

Figure 2–43	Graphical solution for the water table contribution using the Anat Solution	2–160
Figure 2–44	Diagram of the moisture release curve for a sandy clay loam soil using the method of Brooks and Corey	2–162
Figure 2–45	Procedure to determine the characteristic parameters for the Brooks and Corey functions	2–162
Figure 2–46	Distribution of field application depth indicating adequacy of irrigation	2–170
Figure 2–47	Distribution for two irrigation systems having equal adequacy but different uniformity and application efficiency	2–171
Figure 2–48	Distribution for two irrigation systems having equal uniformity but different adequacy and application efficiency	2–172
Figure 2–49	Application efficiency as related to the coefficient of uniformity and the percent of the area that is deficitly irrigated	2–174
Figure 2–50	Method to estimate seepage losses from irrigation delivery systems	2–186
Figure 2–51	Frequency distribution of mean daily ET_c of ryegrass for each month in a coastal California Valley	2–197
Figure 2–52	Log-normal probability distribution to smooth extreme values for daily ET_c data	2–201
Figure 2–53	Weibull transform for smoothing annual maximum ET_c data to predict the design net capacity required	2–201
Figure 2–54	Ratio of mean peak and mean monthly ET_c for different climates during months of peak water use	2–203
Figure 2–55	Shortage and surplus periods for a system where the capacity is less than the average ET_c during a peak water use period	2–204
Figure 2–56	10-day ET_c, rain and soil water deficit, and the soil water depletion pattern over a growing season as affected by gross system capacity	2–206

Figure 2–57	Design net capacity required for corn grown in eastern Colorado to maintain soil water depletion abovea specified depletion for three design probabilities	2–207
Figure 2–58	Checkbook scheduling method	2–210
Figure 2–59	Average daily water use during the season for three crops in North Dakota	2–211
Figure 2–60	Irrigation cycle time, or irrigation interval, and its effect on the soil water depletion at the starting and stopping positions of an irrigation system	2–212
Figure 2–61	Earliest and latest dates to irrigate for a system that applies 1 inch of net irrigation per application and has an allowable depletion of 3 inches, assuming the irrigation interval is 3 days	2–213
Figure 2–62	Example of regional ET_c data for irrigation scheduling	2–215
Figure 2–63	Processes involved in sizing irrigation projects	2–221
Figure 2–64	System capacity curve for a conveyance system	2–222
Figure 2–65	Delivery system layout for a farm served by a large lateral canal	2–223
Figure 2–66	An evaluation form for water conservation inventories of irrigation systems	2–226
Figure 2A–1	Crop growth stage coefficient curve for alfalfa	2–235
Figure 2A–2	Crop growth stage coefficient curve for avocados	2–236
Figure 2A–3	Crop growth stage coefficient curve for dry beans	2–237
Figure 2A–4	Crop growth stage coefficient curve for snap beans	2–238
Figure 2A–5	Crop growth stage coefficient curve for sugar beets	2–239
Figure 2A–6	Crop growth stage coefficient curve for citrus	2–240
Figure 2A–7	Crop growth stage coefficient curve for corn (grain)	2–241
Figure 2A–8	Crop growth stage coefficient curve for corn (silage)	2–242
Figure 2A–9	Crop growth stage coefficient curve for sweet corn	2–243
Figure 2A–10	Crop growth stage coefficient curve for cotton	2–244

Figure 2A–11	Crop growth stage coefficient curve for spring grain	2–245
Figure 2A–12	Crop growth stage coefficient curve for grapes	2–246
Figure 2A–13	Crop growth stage coefficient curve for melons and cantaloupes	2–247
Figure 2A–14	Crop growth stage coefficient curve for deciduous orchards	2–248
Figure 2A–15	Crop growth stage coefficient curve for pasture grasses	2–249
Figure 2A–16	Crop growth stage coefficient curve for peas	2–250
Figure 2A–17	Crop growth stage coefficient curve for Irish potatoes	2–251
Figure 2A–18	Crop growth stage coefficient curve for grain sorghum	2–252
Figure 2A–19	Crop growth stage coefficient curve for soybeans	2–253
Figure 2A–20	Crop growth stage coefficient curve for tomatoes	2–254
Figure 2A–21	Crop growth stage coefficient curve for small vegetables	2–255
Figure 2A–22	Crop growth stage coefficient curve for walnuts	2–256
Figure 2A–23	Crop growth stage coefficient curve for winter wheat	2–257

Examples

Example 2–1	Dew point	2–15
Example 2–2	Vapor pressure deficit	2–16
Example 2–3	Wind speed computations	2–20
Example 2–4	Clear sky radiation	2–25
Example 2–5	Outgoing longwave radiation	2–28
Example 2–6	Outgoing longwave radiation for a clear sky	2–29
Example 2–7	Net outgoing longwave radiation	2–29
Example 2–8	R_s estimate	2–34

Example 2–9	Daily soil heat flux	2–36
Example 2–10	Monthly soil heat flux	2–37
Example 2–11	Penman-Monteith method	2–48
Example 2–12	ET_o—Radiation method	2–53
Example 2–13	FAO Blaney-Criddle	2–57
Example 2–14	Local calibration of a pan coefficient	2–65
Example 2–15	Basal crop coefficient	2–71
Example 2–16	Water stress factor	2–84
Example 2–17	Wet soil surface evaporation	2–87
Example 2–18	Average crop coefficient	2–89
Example 2–19	Nongrowing season crop coefficient	2–91
Example 2–20	Growth adjustment	2–96
Example 2–21	Leaching requirement	2–118
Example 2–22	Leaching requirement calculations	2–120
Example 2–23	Using table 2–46 to estimate the growing season effective precipitation	2–153
Example 2–24	Anat's Solution	2–161
Example 2–25	Determining the gross application for graded furrow irrigation	2–177
Example 2–26	Use of the application efficiency table for graded border irrigation	2–178
Example 2–27	Seepage loss	2–184
Example 2–28	Seasonal irrigation requirement when leaching is unnecessary	2–187
Example 2–29	Seasonal irrigation requirement when leaching is needed	2–190
Example 2–30	Seasonal irrigation requirement for an arid area	2–193
Example 2–31	Seasonal irrigation requirement for a surface system	2–194

Example 2–32	Farm capacity	2–196
Example 2–33	Peak evapotranspiration frequency analysis	2–199
Example 2–34	Weibull distribution	2–200
Example 2–35	Peak evapotranspiration	2–202
Example 2–36	System capacity for corn in eastern Colorado	2–207
Example 2–37	Irrigation scheduling	2–214
Example 2–38	Continuous delivery system	2–218
Example 2–39	Rotational delivery system	2–219

Sample Calculations

Sample calculation 2A–1	Estimate of average daily, monthly, and seasonal consumptive-use by corn (harvested for grain) at Raleigh, North Carolina, latitude 35°47' N	2–233
Sample calculation 2A–2	Estimate of average daily, monthly, and seasonal consumptive use by alfalfa at Denver, Colorado	2–234

Chapter 2 Irrigation Water Requirements

623.0200 Water requirements

(a) Introduction

Irrigated agriculture is facing new challenges that require refined management and innovative design. Formerly, emphasis centered on project design; however, current issues involve limited water supplies with several competing users, the threat of water quality degradation through excess irrigation, and narrow economic margins. Meeting these challenges requires improved prediction of irrigation water requirements.

Irrigation water requirements can be defined as the quantity, or depth, of irrigation water in addition to precipitation required to produce the desired crop yield and quality and to maintain an acceptable salt balance in the root zone. This quantity of water must be determined for such uses as irrigation scheduling for a specific field and seasonal water needs for planning, management, and development of irrigation projects.

The amount and timing of precipitation strongly influence irrigation water requirements. In arid areas, annual precipitation is generally less than 10 inches and irrigation is necessary to successfully grow farm crops. In semiarid areas (those typically receiving between 15 to 20 inches of annual precipitation), crops can be grown without irrigation, but are subject to droughts that reduce crop yields and can result in crop failure in extreme drought conditions.

Subhumid areas, which receive from 20 to 30 inches of annual precipitation, are typically characterized by short, dry periods. Depending on the available water storage capacity of soils and the crop rooting depth, irrigation may be needed for short periods during the growing season in these areas.

In humid areas, those receiving more than 30 inches of annual precipitation, the amount of precipitation normally exceeds evapotranspiration throughout most of the year. However, drought periods sometimes occur, which reduce yield and impair quality, especially for crops grown on shallow, sandy soils or that have a shallow root system. Irrigation is not needed to produce a crop in most years, but may be needed to protect against an occasional crop failure and to maintain product quality.

A unified procedure is needed to predict irrigation water requirements for the diverse soils, climates, and crops that are of interest to the Soil Conservation Service and its clients. Irrigation water requirement information is needed in all aspects of irrigation design and management. Procedures to estimate the irrigation water requirement for this broad range of needs are presented in this chapter.

(b) Irrigation requirements

The primary objective of irrigation is to provide plants with sufficient water to obtain optimum yields and a high quality harvested product. The required timing and amount of applied water is determined by the prevailing climatic conditions, the crop and its stage of growth, soil properties (such as water holding capacity), and the extent of root development. Water within the crop root zone is the source of water for crop evapotranspiration. Thus, it is important to consider the field water balance to determine the irrigation water requirements.

Plant roots require moisture and oxygen to live. Where either is out of balance, root functions are slowed and crop growth reduced.

All crops have critical growth periods when even small moisture stress can significantly impact crop yields and quality. Critical water needs periods vary crop by crop. Soil moisture during the critical water periods should be maintained at sufficient levels to ensure the plant does not stress from lack of water.

(1) Soil-water balance

Producing optimal yield requires that the soil-water content be maintained between an upper limit at which leaching becomes excessive and a lower point at which crops are stressed. For irrigation management, the acceptable soil-water range is generally defined using the available soil-water concept which is the difference between the field capacity and the permanent wilting point. *Field capacity* is defined as the water content at which drainage becomes negligible on a free draining soil. The minimum soil-water

content is defined when plants permanently wilt and is called the *permanent wilting point*. The soil water stored between field capacity and the permanent wilting point is called the total available water or *available water capacity* (AWC).

An allowable depletion is generally defined for irrigation management. The allowable depletion is a management decision based on the grower's production objectives and is referred to as the Management Allowed Depletion (MAD). This is the driest soil-water content that is allowed before irrigation so that undesirable crop water stress does not occur. To prevent reduced yield or quality, the crop should be irrigated before a given percentage of the available water in the root zone has been used by the crop. Historically, an allowable depletion of between 30 and 60 percent of the AWC has been used for management purposes. The soil can be irrigated before allowable depletion is reached if the amount of water applied does not cause the soil water in the crop root zone to exceed field capacity.

Maintaining the soil water within the acceptable range requires information about the addition and extraction of water to the crop root zone. The major processes affecting the soil-water balance are illustrated in figure 2–1. For design and management purposes, the field water balance can be written mathematically as:

$$F_g = ET_c + D_P + RO - P - GW + SD_L - \Delta SW \qquad [2–1]$$

where:

F_g = gross irrigation required during the period
ET_c = amount of crop evapotranspiration during the period
D_p = deep percolation from the crop root zone during the period
RO = surface runoff that leaves the field during the period
P = total precipitation during the period
GW = ground water contribution to the crop root zone during the period
SD_L = spray and drift losses from irrigation water in air and evaporation off of plant canopies
ΔSW = change in soil water in the crop root zone during the period

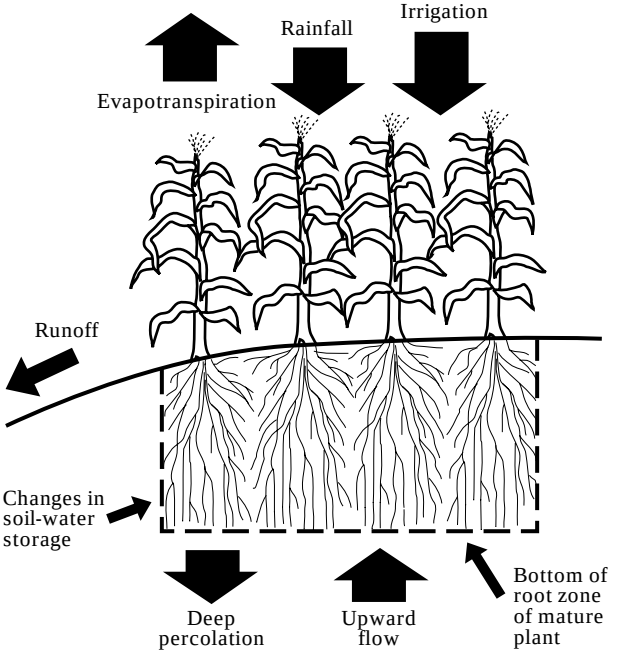
The unit on each of the terms of the water balance is volume per unit area or units of length or depth of water.

The time over which the water balance is computed is extremely important. A monthly time step may be satisfactory for preliminary planning purposes, but most irrigation scheduling procedures require a daily time step to predict irrigation dates. In any case, the sum of the irrigation depths over the growing season forms the basis for determining the annual irrigation water requirements.

Equation 2–1 is the basis for the determination of the Water Balance/Budget development process. It can also be used for a long-term (yearly, multiyear) evaluation of "what water goes where" for determining contributions to downstream surface water and ground water. It can be applied to a field, farm, or group of farms.

A flow chart showing the calculation of irrigation water requirements in equation 2–1 is given in figure 2–2. Detailed discussion of each of the components is provided in other parts of this chapter. Locations of the procedures within chapter 2 are given in table 2–1.

Figure 2–1 Diagram of the soil-water balance of a crop root zone

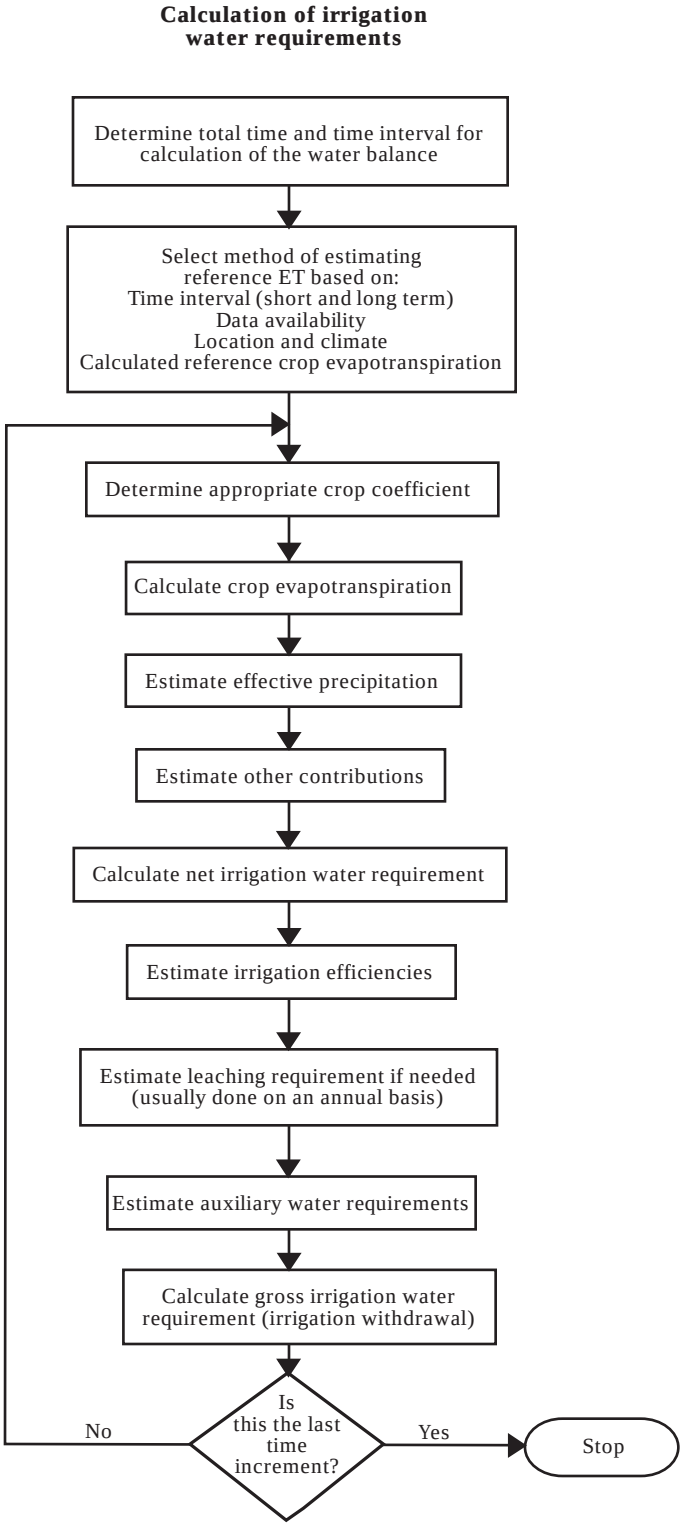


Some items in the process shown in figure 2–2 should be determined or supported by making local field evaluations and onsite monitoring. The values displayed in this chapter are best estimates and generally show a range. They must be supported with good field judgment and local ground truthing. Most surface irrigation systems are operated and managed in a manner that allows runoff or deep percolation, or both, to occur, and all losses are nearly economically or physically impossible to eliminate. With most sprinkler systems, losses because of evaporation and wind drift are present and difficult to control. Local physical site conditions will vary; however, the estimated values included in this chapter are based on well managed irrigation systems and average site conditions.

Table 2–1 Locations of procedures to estimate irrigation water requirements

Process	Location of procedure
Crop water use	623.0201
Climatic processes	623.0202
Reference crop evapotranspiration	623.0203
Crop coefficients	623.0204
Leaching requirements	623.0205
Auxiliary water needs	623.0206
Effective precipitation	623.0207
Water table contributions	623.0208
Irrigation efficiency	623.0209
Onfarm irrigation requirements	623.0210
Project requirements	623.0211

Figure 2–2 Flow chart to compute irrigation water requirements



623.0201 Crop water use

(a) Introduction

The determination of irrigation water requirements and irrigation schedules requires an accurate estimate of the crop water use rate. Daily and weekly crop water use estimates are needed to schedule irrigations, while longer term estimates are needed to specify the irrigation, storage, and conveyance system capacities. Annual water use is often required to size irrigation reservoirs and establish water rights. Therefore, a procedure to predict both the short- and long-term rates of water use by a multitude of crops in varying climates is needed.

This section provides an overview of the processes affecting the rate of crop water use and methods to measure crop water use. It explains the general procedures used to estimate crop water use from climatic data. Procedures to actually compute crop water use rates are then presented in sections 623.0202, 623.0203, and 623.0204.

(b) Evapotranspiration processes

Plants need water for growth and cooling especially on sunny days that have hot, dry winds. Plants extract water from the soil and transport the water to the plant leaves. Small apertures (stomata) located on the upper and lower surfaces of the leaves allow for the intake of carbon dioxide required for photosynthesis and plant growth. Water vapor is lost from the plant leaves by evaporation in the stomatal cavity and the flow of the water vapor through the stomata and into the atmosphere. This process is called transpiration. A considerable amount of energy is required to evaporate the water in the stomatal cavity. If the water did not evaporate, the energy would be used to heat the plant. Without transpiration, plants could reach lethal temperatures.

Plant leaves can be coated with liquid phase of water following rain or sprinkler irrigation or because of dew formation. Water on the plant leaves will rapidly evaporate following the deposition period. However, evaporation from the plant canopy serves the same cooling effect as transpiration.

Water in the soil also evaporates as solar energy or hot, dry winds reach the soil surface. Initially, evaporation from a wet soil surface progresses at a maximum energy limiting rate. As the soil surface dries because of evaporation, water below the soil surface moves upward by capillary action. As soil dries the rate of water flow in the soil decreases. Thus, as evaporation continues, there is more resistance to water flow and eventually the rate of soil-water flow limits evaporation. Where the rate of soil-water flow limits evaporation, excess energy is at the soil surface. The energy not used to evaporate water then heats the soil and air just above the soil surface. If this process continues, the soil and air become quite hot, as in desert climates.

As the soil dries, freewater in the pore space is used first. The remaining soil water is held to the soil particles by various chemical and physical bonds and is more difficult to extract. As soil water decreases, the water with the strongest bond is more difficult for roots to absorb. Water in the soil held at more than the permanent wilting point tension (15 atmos) is held tightly to the soil particles and is not readily available to the plant.

Evaporation of water from the soil and plant surfaces and transpiration from the stomatal cavities of plants account for more than 98 percent of the crop water use of most plant species. Evaporation and transpiration are difficult to measure because the rate of water vapor movement from several surfaces into a dynamic environment varies with time. The process of making measurements can alter the local climate around the plant and change the actual rate of evaporation or transpiration. Therefore, for most irrigation applications, evaporation and transpiration fluxes are combined and are called evapotranspiration.

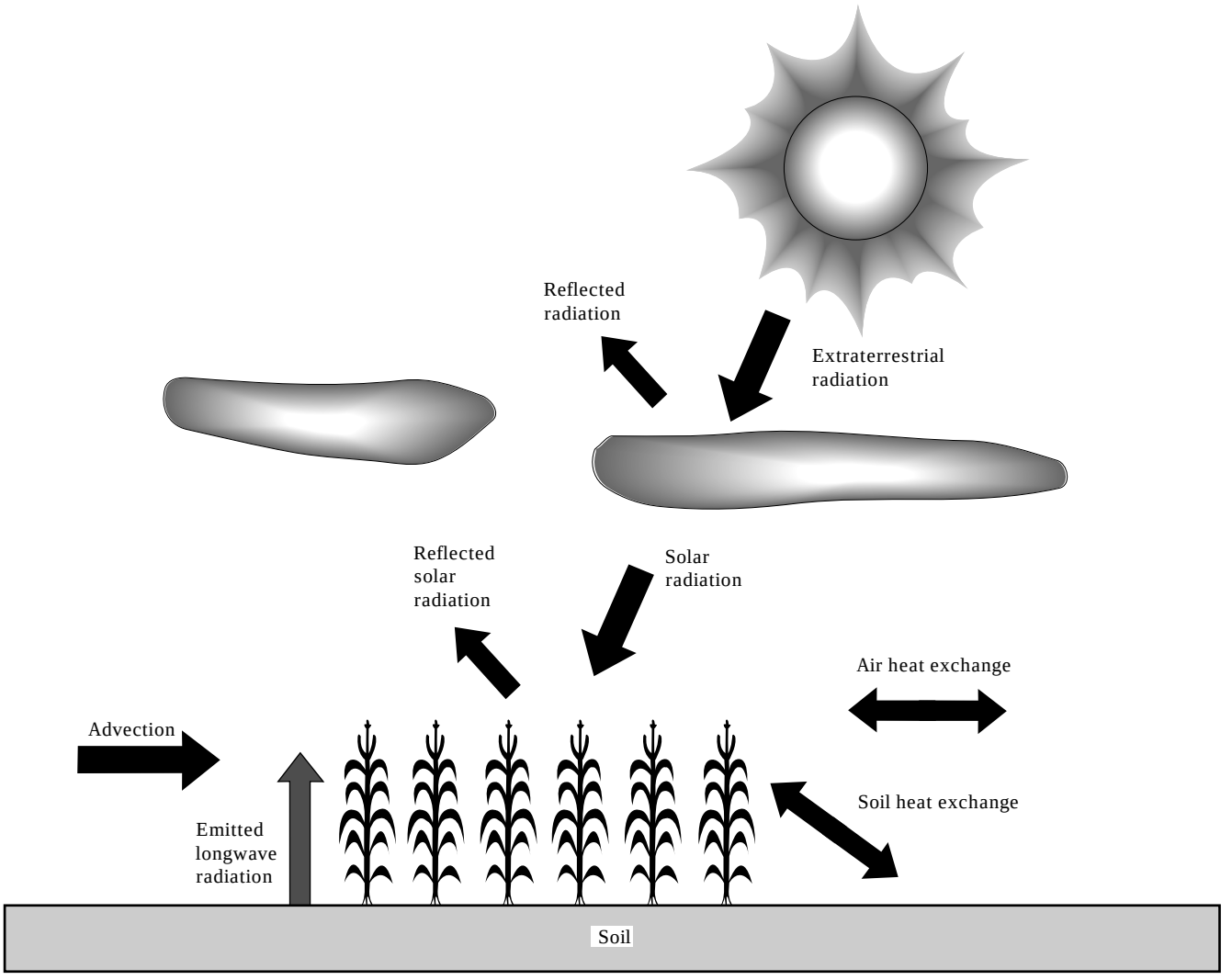
Because evapotranspiration is the loss of water vapor from both plant and soil surfaces, many methods of estimating crop water use depend upon determining the rate that liquid water is converted to water vapor. This process, called evaporation or vaporization, requires energy. For example, the solar energy absorbed by a plant on a bright, sunny summer day would be adequate to evaporate enough water to cover the soil surface to a depth of about 0.4 inch. For an area of 1 acre, the amount of water lost on such a day would be about 11,000 gallons. Thus, the evapotranspiration process requires a large amount of water, which requires a great deal of energy.

The energy available for evapotranspiration from a crop system can come from several sources (fig. 2–3). The largest energy source is from solar radiation. The extraterrestrial radiation from the sun varies during the season, but is very constant from year to year, primarily depending on latitude. However, a large amount of the extraterrestrial radiation is absorbed or reflected in the atmosphere. The energy that ultimately reaches the crop canopy, generally called solar radiation, is available in the shortwave length band (i.e., from 0.1 to 5 microns) of the solar radiation spectrum.

Crop and soil surfaces reflect some of the incoming solar radiation. The portion of the solar radiation absorbed varies depending primarily on the color and other properties of the absorbing surface. The solar radiation that is reflected back to the atmosphere is generally described using a term called the albedo. The albedo (α) is the ratio of the reflected radiation (R_r) to incoming radiation (R_s):

$$\alpha = R_r/R_s$$

Figure 2–3 Energy available for evapotranspiration from crop systems



Representative albedo values for various crops and soils are summarized in table 2–2. The albedo values from this table indicate that about 20 to 25 percent of the incoming solar energy is reflected by plant and soil surfaces. A commonly used albedo value for practical irrigation management is 23 percent. In this case the remaining 77 percent of the solar radiation is absorbed and is primarily used for evapotranspiration.

The second component of the radiation balance is called longwave radiation, which occurs in the wavelength band from 3 to 70 microns. This is energy transfer because of the temperature difference between two objects. For field crops, the two bodies exchanging energy are difficult to define. In general, the two surfaces are the crop-soil surface and the outer atmosphere. The rate of longwave energy emission is proportional to the absolute temperature of the surface raised to the fourth power. Because the outer atmosphere is cold relative to the Earth's surface, the longwave energy is lost from the plant-soil system.

The amount of radiant energy available for evapotranspiration, called net radiation (R_n), is the sum of the absorbed solar radiation minus the emitted longwave radiation. In many locations, net radiation is the dominant energy term and may be sufficient to estimate evapotranspiration, especially for long time periods. Procedures to compute the amount of net radiation will be presented in a later section.

Advection is the transfer of heat by horizontal movement of air. The amount of heat energy transferred depends on the wind speed and the humidity of the air, which is an index of the amount of water vapor in the air. The humidity, however, depends on the temperature and barometric pressure. The concept of vapor pressure is used to describe the evaporative capacity of the air.

Table 2–2 Albedo (percentage of incoming radiation reflected back to the atmosphere) for natural surfaces (Rosenberg 1974)

Fresh snow	0.80 – 0.95
Old snow	0.42 – 0.70
Dry Sandy soils	0.25 – 0.45
Dry clay soils	0.20 – 0.35
Peat soils	0.05 – 0.15
Most field crops	0.20 – 0.30
Forests, deciduous	0.15 – 0.20
Forests, coniferous	0.10 – 0.15
Forests, deciduous with snow on ground	0.20

Dalton's law of partial pressure states that the pressure exerted by a mixture of ideal gases in a given volume is equal to the sum of the pressures exerted by each individual gas if it alone occupied the given volume. Because moist air behaves as a nearly ideal gas and obeys Dalton's law, the part of the barometric pressure caused by water vapor in the air can be considered independent from the other gases in the air. The partial pressure exerted by water vapor, called the vapor pressure of the air (e), is usually expressed in units of millibars (mb). For reference purposes, a pressure of 1 pound per square inch is equivalent to about 69 millibars.

At an air-water interface, water molecules continually flow from the water into the air and from the air back into the liquid surface. If the air is dry, more molecules leave the liquid than enter, resulting in evaporation. If air in a sealed container is left in contact with water long enough, the rate of molecules leaving and entering the liquid surface will reach equilibrium. Where equilibrium exists with pure water, the air is saturated with water vapor. The partial pressure exerted by the vapor at this equilibrium condition is defined as the saturated vapor pressure of the air (e^o). The saturated vapor pressure is strongly dependent on temperature. The ratio of the actual vapor pressure to the saturated vapor pressure (e / e^o) is the relative humidity of the air.

Air in the soil matrix and within the stomatal cavities is often saturated and thus has a high vapor pressure. If air surrounding the plant and soil is at the same temperature as the crop and soil, but much drier, it will have a lower vapor pressure. Water vapor moves from locations of high vapor pressure toward those with low vapor pressure. If the air around the crop is contained within a chamber, it eventually becomes saturated with water vapor. At that time, evapotranspiration is negligible because the air cannot hold any additional water. If the saturated air is replaced with new dry air, evapotranspiration resumes. The more rapidly the air is exchanged and the drier the air, the higher the evapotranspiration rate. In windy, arid

locations, advection may provide as much energy for evapotranspiration as net radiation. However, in humid locations or in areas with little wind, the contribution of advection to evapotranspiration may be quite low and can be ignored for practical crop water use estimates.

Two other energy sources for evapotranspiration are the exchange of heat between the crop and the soil or between the crop and the air surrounding the crop. For example, if the soil is warmer than the crop, energy is transferred from the soil to the crop. This energy may increase transpiration. Conversely, if the canopy is warmer than the soil, energy flows toward the soil and transpiration may thus be reduced. The same energy transfer can occur between the crop and air. Crops that are not stressed for water are generally cooler than the surrounding air during the middle of the day. However, if stressed for water, the crop will often be warmer than the surrounding air.

The heat exchange between the crop and the soil, or air, is primarily important for short-term evapotranspiration estimates and is generally cyclical. On one day, the soil may receive heat, but the next, the crop may be cooler and the soil emits energy. In the long run, the net contribution of these heat exchanges to evapotranspiration is generally small.

The combined energy input into the crop-soil system can be summarized by:

$$E_I = R_n + A_d \pm S_f \pm A_h \qquad [2–2]$$

where:

E_I = net energy input
R_n = net radiation (from solar and longwave radiation)
A_d = advection, (from air)
S_f = soil heat flux
A_h = air heat flux

The basic energy balance for a soil-crop system can be written as:

$$E_I = E_{et} + P_s + A_H + S_H + C_H \qquad [2–3]$$

where:

E_{et} = energy available for evapotranspiration
P_s = energy used for photosynthesis
A_H = energy used to heat air
S_H = energy used to heat soil
C_H = energy used to heat crop

Solving for E_{et} by combining equations 2–2 and 2–3 results in:

$$E_{et} = R_n + A_d \pm S_f \pm A_h - P_s - A_H - S_H - C_H \qquad [2–4]$$

When energy is introduced into the crop system, several processes occur. In response to energy inputs, the soil, air, and crop temperatures increase. A small part of the energy (about 2%) is used for photosynthesis and other reactions that occur in crop growth. The two primary energy sinks are evaporation and transpiration, or jointly evapotranspiration.

The energy balance equation describes the driving force for evapotranspiration. However, two additional factors are involved in the evapotranspiration process. First, there must be a source of water in the soil and plant to supply that used in the evapotranspiration process. Second, water must move from the soil to the point where evaporation occurs, or into and through the plant to the stomatal cavity where transpiration occurs. If the soil is dry, more resistance to water transport in the soil occurs. Also, as plants are stressed, the stomata close and the resistance to water flow in the plant increases. Therefore, evapotranspiration can be limited by either the amount of available energy or water availability in the soil.

When crop evapotranspiration (ET_c) is limited by water availability, the crop, soil, or air temperature must increase to maintain the energy balance. Changes in ET_c rates and crop temperatures are very dynamic. The values fluctuate during the day in response to small changes in the climate and in response to the water supply. Complex methods and models exist (Norman and Campbell 1982 and Campbell 1977) to calculate ET_c frequently throughout the day. These complex methods require a large number of parameters that are difficult to predict. Thus, they are primarily research tools. However, the energy balance equation and the resistance of water flow have been used for practical methods of computing or measuring ET_c. Various procedures for estimating ET_c are in sections 623.0202, 623.0203, and 623.0204.

(c) Direct measurement of evapotranspiration

(1) Aerodynamic methods

Aerodynamic methods involve measuring the rate of water vapor movement above the crop canopy. The vapor pressure of the air and the air flow velocities can be measured at several levels above a uniform plant canopy. By combining these measurements, the instantaneous evapotranspiration rate can be determined, and through integration of these frequent measurements, the rate of evapotranspiration for a day can be computed. Because this technique requires specialized and accurate equipment, it is generally only used for a week or less during the growing season. It is certainly not a method for unattended measurements.

A primary problem with this technique is the erratic movement of air above a crop canopy. This variability can be reduced by confining measurements to changes of air properties within a chamber placed over the location where ET_c will be measured. Probably the biggest drawback with chamber methods is that plants respond rapidly to the presence of the chamber, which alters the local climate. If the chamber remains over the plant too long, the ET_c rate and other plant responses change. Thus, chamber methods can only be used to make measurements for relatively short periods.

Another aerodynamic method involves the use of the energy balance equation (equation 2–4). This equation can be simplified by assuming that net radiation is the principal energy input. If it is also assumed that the energy used for photosynthesis, soil heating, and canopy heating is negligible, the energy balance can be written as:

$$E_{et} = R_n - A_H \qquad [2–5]$$

A term called the Bowen ratio (β) is defined as:

$$\beta = \frac{A_H}{E_{et}} \qquad [2–6]$$

The Bowen ratio is the ratio of the amount of energy used to heat the air relative to the amount used to evaporate water. Combining equations 2–5 and 2–6 gives:

$$E_{et} = \frac{R_n}{(1+\beta)} \qquad [2–7]$$

Equipment has been developed to measure the Bowen ratio of the air that can be used with equation 2–7, along with the amount of energy required to evaporate water to estimate evapotranspiration. The primary problem with the Bowen ratio method is that advection is ignored. In many areas, this is an intolerable assumption.

(2) Soil-water methods

As soil water is the ultimate source of water used during the evapotranspiration process, several methods have been used to relate changes in soil water to crop water use. Conservation of the mass of water in the crop root zone or the soil-water balance can be used to estimate crop water use. The primary components of the soil-water balance are illustrated in figure 2–1. For onfarm irrigation, these concepts can be expressed in a revised form of the soil-water balance equation as:

$$SW_e = SW_b + P + F_g + GW - RO - D_p - ET_c \qquad [2–8]$$

where:

SW_e = amount of soil water in the root zone at the end of a period
SW_b = amount of soil water in the root zone at the beginning of a period
P = total rain during the period
F_g = gross net irrigation during the period
GW = ground water contribution to water use during the period
RO = surface runoff that leaves the area during the period
D_p = deep percolation from the root zone during the period
ET_c = amount of crop evapotranspiration during the period

The ET_c or some time periods can be estimated if all other terms in equation 2–8 are measured or if sites are selected to minimize their contributions. If the ground water table is not present or is more than several feet below the soil surface, the contribution from ground water can generally be ignored. If a level location can be found, then surface runoff can be minimized. Dikes around the area can be constructed if runoff from adjacent areas is significant. Rain and

irrigation from sprinklers generally are measured with rain gauges. Measuring devices are needed for surface irrigation applications. The soil-water content is usually measured using neutron scattering techniques. Deep percolation is the most difficult component of equation 2–8 to measure.

The primary problem with the field water balance method of measuring ET_c is that several measurements must be made repetitively during the season. Because of the accuracy of the measurements, 1 week is generally the shortest reasonable period for a soil-water balance. Also, if deep percolation or runoff is significant, the application of the field water balance method is limited. Thus, for such problems or where frequent ET_c rates are needed, the representative field area generally is isolated. Lysimeters are the most common methods used to isolate the field area. They are small, fully contained tanks where changes in soil-water content caused by irrigations, rainfall, and crop evapotranspiration can be precisely measured.

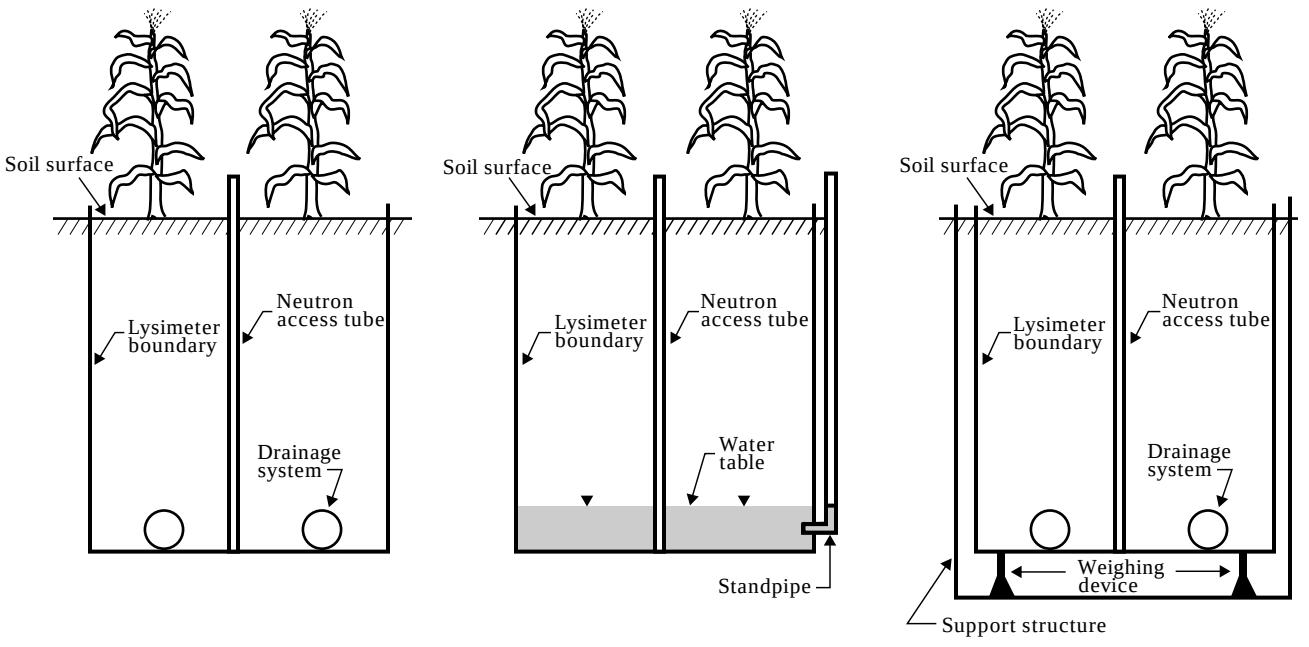
(3) Lysimetry

Various types of lysimeters have been designed, constructed, and used throughout the world (fig. 2–4). One type is a nonweighing lysimeter that has an access tube installed to measure soil-water changes with neutron scattering techniques (fig. 2–4a). This lysimeter is identical to the field water balance method except that deep percolation is prevented by the bottom of the lysimeter. The controlled drainage system can be used to quantify drainage periodically.

A commonly used lysimeter in humid regions is called a water table lysimeter (figure 2–4b). With this design, deep percolation is prevented and a water table is maintained in the lysimeter. Changes in soil water and the elevation of the water table are measured along with other soil-water balance terms.

The most elaborate type of lysimeters is a weighing lysimeter (figure 2–4c). It is similar to the others except that weighing devices used to measure water

Figure 2–4 Schematic diagram of three types of lysimeters used to measure crop evapotranspiration



a. Nonweighing lysimeter **b. Water table lysimeter** **c. Weighing lysimeter**

loss are installed below the lysimeter. The types of weighing devices vary considerably. The most sophisticated have high precision and can be used to measure small changes of weight. A good description of precision lysimeters is given by Marek et al. (1988).

Generally, the accurate lysimeters are precision weighing lysimeters. They have a counter balanced weighing system, resulting in a measurement accuracy approaching 0.001 inch of evapotranspiration. The high accuracy is required for daily measurements because the weight change as a result of ET_c is generally small compared to the total weight of the lysimeter and its contents. Less precise, noncounter balanced weighing lysimeters have been used to make longer term measurements. Of course, the cost of weighing lysimeters is generally much higher than that for other designs, especially for precision weighing lysimeters.

Lysimeters pose several problems in addition to their cost. The use of lysimeters to measure ET_c has been summarized by Allen et al. (1991). The best lysimeters, termed monolithic lysimeters, are those filled with an undisturbed soil column. If they are large, their filling can be difficult and expensive. Regular and careful maintenance of the lysimeter and the surrounding area is required to maintain the desired accuracy. Lysimeters can be used to measure ET_c for longer periods if precipitation and irrigation are measured. Some precision lysimeters can directly measure water additions by weight changes. Less precise lysimeters require that these additions be measured in other ways.

Measurement error and spatial variability can be significant when using lysimeters. Thus, to have confidence in the ET_c measurements, several lysimeters are needed. The more precise the lysimeter, the smaller the number of lysimeters needed. In general, lysimeters are good to excellent research tools, but presently are too complex and labor intensive to use for onfarm water management.

(4) Plant monitoring methods

The transpiration rate for crops can be measured using several techniques. One method uses a porometer. With this instrument, a small chamber is clamped onto a growing plant leaf and measurements of changes in the humidity and temperature of the air within the chamber can be used to compute the amount of transpiration during that period. The transpiration rate and other plant responses occur very rapidly because of external factors. Therefore, the porometer can only remain on the leaf for a few minutes.

Another limitation of the porometer is that only a small part of one leaf is used for measurement. Characterizing the transpiration for an entire crop canopy requires numerous measurements. Further, these measurements only provide instantaneous transpiration rates. Generally, irrigation management requires crop water use for daily and longer periods. Thus, porometers are primarily used in experiments to investigate plant response to stress and not for crop water use estimates.

A second method uses infrared thermometers to predict transpiration based upon the difference between the crop temperature and the air temperature. These thermometers are primarily used to detect when the plant is under stress and to predict irrigation timing. However, if the incoming solar radiation and other energy terms are known, the ET_c rate can be estimated using the techniques of Hatfield (1983) and Jackson (1982). These techniques are complex and require extensive calculation as well as continuous monitoring of plant temperature. The infrared plant monitoring method can help in scheduling and managing irrigation, but it needs further development to estimate ET_c.

(5) Soil evaporation measurements

Several methods have been developed to measure soil evaporation. One method uses mini- or micro-lysimeters, which are small cylinders (generally 2 to 8 inches in diameter and 2 to 8 inches long) that are filled in a monolithic style. The devices are capped on the bottom and placed back in the field soil. Daily weighing determines the evaporation rate, and in some cases daily irrigation maintains the soil-water content in the lysimeter similar to the surrounding field conditions. In other cases the same lysimeter has been used for a longer period of drying. Lysimeters require extensive labor to measure daily evaporation and extreme care so that soil-water conditions are representative. The distribution of lysimeters must also be carefully considered where the plant canopy does not fully shade the soil.

The second method of measuring evaporation uses a soil surface psychrometer as described by Seymour and Hsiao (1984). This instrument is a smaller version, similar to the chambers used to measure ET_c. The unit

is placed on the soil surface, and the change of water vapor in the chamber is measured over time thereby providing an instantaneous rate of soil evaporation.

(6) Regional evapotranspiration methods

In some cases estimates are needed of regional evapotranspiration that occurs over a wide area. These estimates can be made indirectly using the water balance approach by measuring the inflow and outflow of ground water and surface water along with the changes of water storage in the basin. The difference in these terms represents the evapotranspiration over the entire area. Generally, the mixture of land uses and reservoir storage is not considered specifically. These methods require extensive monitoring and several years of data to provide acceptable accuracy. Generally, basin water balance techniques are only accurate for relatively long-term evapotranspiration estimates.

A second method to determine regional evapotranspiration using infrared images from satellites and other high altitude systems is currently being developed. The techniques used to predict evapotranspiration for these large regions are based on the same concepts as the plant monitoring system using a hand held infrared thermometer. The complex map of temperature of the Earth's surface must be processed to integrate water use across the area. Once perfected, these methods may provide useful information on the rate of evapotranspiration at the time the image is taken. However, much additional work is needed to estimate the total evapotranspiration for a shorter period. This will be especially difficult if satellite images are not available on a frequent basis. Their projected use at the current time is the determination of the crop water status for a multitude of crops and for updating yield estimates.

Regional evapotranspiration methods are generally used for hydrological or crop forecasting purposes. Currently, the methods are not refined enough to predict crop water use for fields on a continual basis. That might be possible in the future, but considerable research is still needed before that type of information is available.

(7) Summary

Direct measurement of evapotranspiration requires special equipment and training. The measurements generally are time consuming, have severe limitations, and are too expensive for wide scale use in determining actual crop water use. Generally, the methods require several years of experimentation to determine crop water use. Direct measurement of ET_c is generally not used for irrigation scheduling, design, or management. However, these techniques have been successfully used to develop more practical ways of estimating ET_c. They have been used in research to develop and calibrate several types of equations to compute ET_c for a wide range of conditions. The equations recommended for predicting crop water use are described in sections 623.0202, 623.0203, and 623.0204.

(d) Estimating crop evapotranspiration

Many methods have been developed to estimate the rate of ET_c based on climatic factors. The simplest methods generally use the average air temperature. The most complex methods require hourly data for solar radiation, air temperature, wind speed, and the vapor pressure. Many approaches are between these extremes. All methods of predicting ET_c require some information about the rate of crop canopy development.

After considering various approaches, the reference crop method is recommended for a unified procedure that has proven accurate for many locations. The reference crop evapotranspiration method uses two factors to predict actual crop water use:

$$ET_c = (K_c)(ET_o) \qquad [2–9]$$

where:

ET_c = actual crop evapotranspiration rate
K_c = crop coefficient
ET_o = evapotranspiration rate for a grass reference crop

The reference crop is generally represented by either grass or alfalfa. Well watered and healthy grass clipped to a height of 3 to 6 inches has been widely used. Well watered and healthy alfalfa at least 12 inches tall has been used in the Western United States.

The primary purpose of this publication is to provide a means to compute reasonable estimates of crop water use for irrigation. To reduce confusion and provide consistency, grass will be used for the reference crop

in this chapter. Four methods to predict ET_o are presented in section 623.0203. All methods rely on climatic measurements. Climatic relationships needed to process climatic measurements are presented in 623.0202.

The crop coefficient (K_c) in equation 2–9 relates the actual crop water use to that of the grass reference crop. The value of the crop coefficient generally is small when the plant canopy is small and only partly shades the soil surface. Most of the crop water use at this time is from evaporation from the soil surface. As the canopy develops, more radiation is absorbed by the crop; thus, the transpiration rate of the crop increases. When the crop completely shades the soil surface, the crop coefficient may exceed 1.0. That is, the water use of the actual crop may be larger than that used by the grass reference crop because of the increased leaf area and a taller crop. As the season progresses and the crop begins to senesce, the value of the crop coefficient will begin to decrease.

Crop coefficients depend on specific crops and soil factors. In addition, the water use for daily versus monthly estimates require that the crop coefficient be calculated differently depending on the length of the estimate period. Also, the effect of soil moisture stress and a wet soil surface on the actual crop water use rate may be important for such applications as irrigation scheduling. Finally, methods are needed to verify that the crop coefficient is adjusted for the effects of weather patterns that may cause rapid or delayed crop growth. Because of the importance and unique nature of crop coefficients, they are described in more detail in section 623.0204.

Because the traditional Modified Blaney-Criddle method in SCS Technical Release 21 is used throughout the Western United States, it is described in the appendix to this chapter. In some areas the allotment of water rights is based on this method; therefore, it is important to retain this method. However, because of improved accuracy and consistency, the reference crop techniques are recommended.

623.0202 Climatic relationships and data

(a) Introduction

The crop evapotranspiration rate is determined by the amount of energy available to evaporate water. The amount of energy is represented by the reference crop evapotranspiration rate. Methods that use climatic information to predict the amount of reference crop evapotranspiration have been developed. Generally, the climatic information that is measured at weather stations is not used directly in the methods for computing reference crop evapotranspiration. The climatic properties and relationships used to process data measured at weather stations for computing reference crop evapotranspiration are presented in this section.

An example site is used to illustrate the calculations involved in using the climatic relationships. The site is representative of an area near Dodge City, Kansas. Monthly and annual weather parameters are given for this site in table 2–3.

(b) Barometric pressure

The atmospheric pressure, or barometric pressure, results from the force exerted by the weight of vapors, or gases, in the air. The Earth's gravitational pull is stronger at low elevations than at higher elevations above sea level. Under standard conditions, the average atmospheric pressure at sea level is about 14.7 pounds per square inch (psi), while at an elevation of 2,600 feet above sea level, the mean atmospheric pressure is about 13.4 psi. In evapotranspiration studies, pressures are commonly expressed in units of millibars (mb). One psi is equal to about 69 mb; thus, the atmospheric pressure under standard conditions would be 1,013 mb at sea level and 920 mb at 2,600 feet above sea level. The mean barometric pressure can be calculated by:

$$BP = 1.013\left[1 - \frac{E_{lev}}{145,350}\right]^{5.26} \qquad [2–10]$$

where:
BP = barometric pressure (mb)
E_{lev} = elevation above sea level (ft)

Table 2–3 Average daily value of climatic parameters for an example site near Dodge City, Kansas [1/]—latitude: 37°46' N; longitude: 99°58' W; elevation: 2,600 feet

Month	Air temperature, °F Maximum	Minimum	Mean	Mean dew point	Solar radiation (lang/d)	Sunshine fraction (n/N)	Wind run [2/] (mi/d)	Mean relative humidity (%)	Mean precipitation (in)
January	45	20	32.5	18	255	0.67	260	65	0.46
February	49	23	36.0	23	316	0.66	260	62	0.57
March	55	30	42.5	25	418	0.68	296	60	0.83
April	68	41	54.5	36	528	0.68	296	60	1.67
May	77	51	64.0	49	568	0.68	278	64	3.07
June	88	61	74.5	57	650	0.74	260	61	2.59
July	93	67	80.0	61	642	0.78	244	58	2.25
August	92	66	79.0	59	592	0.78	244	59	2.44
September	83	56	69.5	51	493	0.76	260	56	1.31
October	74	45	59.5	41	380	0.75	244	60	1.20
November	57	30	43.5	29	285	0.70	260	60	0.66
December	45	23	34.0	22	234	0.67	244	64	0.47
Annual	69	43	56.0	39	447	0.71	262	61	17.50

1/ Source: United States Department of Commerce (1977).
2/ Wind speeds were originally measured at a 10 m height, but have been adjusted to a standard height of 2 m for this example.

(c) Air properties

Air is composed of several gases, one of which is water vapor. The amount of water vapor present in air is often characterized using the relative humidity (RH). RH is an index of the amount of water vapor present in the air compared to the maximum amount of water the air could hold at its current temperature. Thus, the relative humidity of the air changes as the temperature of the air changes. If the amount of water vapor in the air remains constant, but the temperature increases, RH decreases because warm air can hold more water vapor than cool air. Because RH is so dependent on temperature, it is not very useful for evapotranspiration calculations. A more useful parameter to describe the amount of water vapor in the air is the vapor pressure (e), which is the partial pressure of the water vapor in the atmosphere.

As the relative humidity increases, the vapor pressure also increases. Where the air is saturated with water vapor, the relative humidity will be 100 percent and the vapor pressure will have reached the maximum value for that temperature. The maximum vapor pressure, called the saturated vapor pressure, is denoted by e°. Similar to relative humidity, the saturated vapor pressure depends on temperature. The saturated vapor pressure can be computed using an equation simplified from that presented by Jensen, et al. (1990):

$$e^\circ = \left(\frac{164.8 + T}{157}\right)^8 \qquad [2–11]$$

where:
e° = saturated vapor pressure (mb)
T = air temperature (°F)

The value of the saturated vapor pressure as a function of air temperature is shown in figure 2–5. This figure also shows the vapor pressure at various relative humidities as a function of temperature.

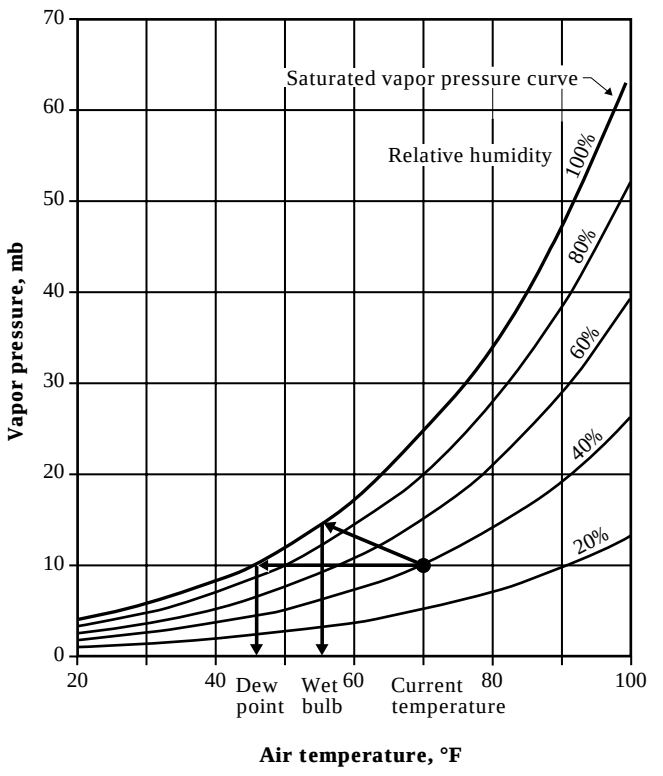
Air generally is not saturated with water vapor (i.e., at 100% relative humidity). An example of air at a temperature of 70 °F and 40 percent relative humidity is shown in figure 2–5. The actual vapor pressure for this condition is about 10 mb. The saturated vapor pressure at 70 °F is 25 mb. Using these data, the relationship between relative humidity and vapor pressure can be illustrated:

$$RH = \left(\frac{e}{e^\circ}\right)100 \qquad [2–12]$$

where:
RH = relative humidity (%)
e = actual vapor pressure (mb)
e° = saturated vapor pressure (mb)

Another important property of air called the dew point temperature is shown in figure 2–5. The dew point is the temperature at which water vapor in the air condenses and forms dew. If air at 70 °F and 40 percent relative humidity was cooled to the dew point (45 °F), water would begin to condense.

Figure 2–5 Relationship of vapor pressure and relative humidity to temperature



The vapor pressure for the current air conditions is the same as the saturated vapor pressure at the dew point temperature. The saturated vapor pressure at the dew point is generally represented by e_d. The dew point vapor pressure can be calculated using the saturated vapor pressure equation and the dew point temperature. In processing data from weather stations, it is necessary to compute the dew point temperature from the measured vapor pressure. Equation 2–11 can be rearranged for this purpose to give:

$$T_d = 157(e)^{0.125} - 164.8 \qquad [2–13]$$

where:
T_d = dew point temperature (°F)
e = vapor pressure of the air (mb)

Example 2–1 illustrates the use of these equations.

The energy available in dry air to evaporate water is characterized by the difference between the saturated vapor pressure of the air and the actual vapor pressure of the air. This difference is called the vapor pressure deficit and is expressed as:

$$e_z^o - e_z$$

The variable e_z^o is the average saturated vapor pressure for the day when measured at a height z above the soil. Several methods have been used to compute e_z^o. The method used in this chapter is to compute the

Example 2–1 Dew point

Given: Suppose a measurement of the air gave the temperature (T) to be 80 °F and the relative humidity (RH) to be 60 percent.

Compute:
a) the saturated vapor pressure (e°),
b) the actual vapor pressure (e), and
c) the dew point temperature (T_d).

Solution:
a) Calculation of saturated vapor pressure e°, use equation 2–11

$$e^\circ = \left(\frac{164.8 + 80}{157}\right)^8$$

$$e^\circ = 34.9 \text{ mb}$$

b) Calculation of the actual vapor pressure e, use equation 2–12

$$RH = \left(\frac{e}{e^\circ}\right)100$$

$$e = e^\circ \frac{RH}{100}$$

$$e = (34.9 \text{ mb}) \times \left(\frac{60}{100}\right)$$

$$e = 20.9 \text{ mb}$$

c) Calculation of the dew point temperature T_d, use equation 2–13

$$T_d = 157(20.9)^{0.125} - 164.8$$

$$T_d = 64.8 \text{ °F}$$

mean saturated vapor pressure for the daily maximum and minimum air temperature:

$$e_z^o = \frac{1}{2}\left(e^o_{T_{max\,z}} + e^o_{T_{min\,z}}\right) \qquad [2–14]$$

where:

$e^o_{T_{max\,z}}$ = saturated vapor pressure for the maximum daily air temperature that is measured at height z

$e^o_{T_{min\,z}}$ = saturated vapor pressure for the minimum daily air temperature that is measured at height z

Example 2–2 helps illustrate the calculation. The actual vapor pressure is equal to the saturated vapor pressure at the daily dew point temperature:

$$e_z = e_d \qquad [2–15]$$

It is very important that this procedure is used to compute the vapor pressure deficit. A shortcut that is sometimes followed is to use the average air temperature to compute $e°_z$. This should **not** be done because the reference crop evapotranspiration will consistently under predict crop water use. Using the average temperature in the vapor pressure deficit (example 2–2) would give $e°_z$ = 29.1 mb. The resulting vapor pressure deficit would then be 29.1 – 15.9 mb = 13.2 mb. This error is very serious especially when the air is dry and the wind speed is high. The procedure used in example 2–2 should be followed in the handbook.

Example 2–2 Vapor pressure deficit

Compute: The average vapor pressure deficit for the example site in June.

Solution: Saturated vapor pressure equation, equation 2–11:

$$\left(\frac{164.8 + T}{157}\right)^8$$

$$\text{maximum air temperature} = 88°\text{F} \rightarrow e^o_{T_{max\,z}} = 45.2 \text{ mb}$$

$$\text{minimum air temperature} = 61°\text{F} \rightarrow e^o_{T_{min\,z}} = 18.3 \text{ mb}$$

$$e_z^o = \frac{1}{2}\left(45.2 + 18.3\right) \text{mb}$$

$$e_z^o = 31.8 \text{ mb}$$

$$\text{dew point temperature} = 57°\text{F} \rightarrow e_z = 15.9 \text{ mb}$$

$$\text{vapor pressure deficit} = \left(e_z^o - e_z\right) = 31.8 - 15.9 \text{ mb}$$

$$= \left(e_z^o - e_z\right) = 15.9 \text{ mb}$$

Some of the methods used to compute reference crop evapotranspiration depend on the slope of the saturated vapor pressure curve with respect to air temperature. The slope of the vapor pressure curve is represented by Δ and can be calculated as:

$$\Delta = 0.051\left(\frac{164.8 + T}{157}\right)^7 \qquad [2–16]$$

where:
Δ = slope of vapor pressure curve (mb/°F)
T = air temperature (°F)

Another necessary parameter for reference crop evapotranspiration methods is the psychrometric constant (γ). This parameter is derived from the use of psychrometers to measure air properties. A psychrometer has two thermometers. One is a traditional thermometer that measures the air temperature. The second thermometer is covered with a wick that is wetted with water when in use. When air is forced past the psychrometer, the wetted thermometer is cooled by the evaporation of water. This temperature, referred to as the *wet bulb* temperature, is denoted by T_w. Water will evaporate until the vapor pressure of the air reaches the saturated vapor pressure at the wet bulb temperature. This process is graphically illustrated in figure 2–5.

When using the psychrometer, the energy to evaporate the water comes from the cooling of the air from the normal, i.e., dry bulb, temperature to the wet bulb temperature. The change of energy can also be represented by the change of vapor pressure by using the psychrometer constant. The result of that expression gives the definition of the psychrometer constant:

$$\gamma_c = \left(\frac{e_w^o - e}{T - T_w}\right) \qquad [2–17]$$

where:
γ_c = psychrometer constant (mb/°F)
e_w^o = saturated vapor pressure at the wet bulb temperature (mb)
e = vapor pressure of the air (mb)
T_w = wet bulb temperature (°F)
T = air temperature (°F)

The psychrometer constant equals a theoretical value called the psychrometric constant (γ) if the psychrometer is perfectly designed and used. The psychrometric constant can be computed as:

$$\gamma = c_p \frac{BP}{0.622\lambda} \qquad [2–18]$$

where
γ = psychrometric constant (mb/°F)
c_p = specific heat of dry air (lang/in/°F)
BP = mean barometric pressure (mb)
λ = heat of vaporization (lang/in of water)

The specific heat is the amount of energy needed to raise a unit of air one degree and equals 0.339 lang/in/°F.

The heat of vaporization of water (λ) is the amount of energy needed to evaporate a unit of water. It depends on the air temperature and is given by:

$$\lambda = 1,543 - 0.796\ T \qquad [2–19]$$

where:
λ = heat of vaporization of water (langs/in)
T = air temperature (°F)

For the air temperature of 70 °F as shown in figure 2–5, the heat of vaporization equals 1,487 langleys per inch. If these conditions were at sea level, where BP=1,013 mb, the psychrometric constant would be 0.37 mb/°F. As shown in figure 2–5, this gives a wet bulb temperature of about 56 °F and a saturated vapor pressure at the wet bulb temperature of 15.3 mb.

(d) Wind relationships

The wind speed profile within and above a crop canopy is illustrated in figure 2–6. The wind speed decreases rapidly with depth into the canopy. Above the crop canopy, the wind speed can be described using a logarithmic profile. To describe the logarithmic profile, the roughness parameter (Z_o) and the zero plane displacement (d) are used. Using these definitions, the wind speed (U) above the crop canopy can be described as:

$$U = \left(\frac{U^*}{k}\right) LN\left(\frac{Z - d}{Z_o}\right) \qquad [2–20]$$

where:
- U = wind velocity at height Z (mi/hr)
- U* = representative friction velocity (mi/hr)
- k = von Karman's constant = 0.41
- LN = natural logarithm
- Z = height above the soil surface (ft)
- Z_o = roughness parameter (ft)
- d = zero plane displacement (ft)

Allen (1986) showed that the roughness parameter and the zero plane displacement were proportional to the crop height:

$$Z_o = 0.01025\, h_c \qquad [2–20a]$$

$$d = \frac{h_c}{18} \qquad [2–20b]$$

where:
- h_c = crop height (in)

The representative friction velocity (U*) is a theoretical parameter representing the characteristics of a crop. The value is difficult to measure and is seldom directly used in practical applications.

Equation 2–20 is not used directly, but instead is used to relate the wind speed at one height to the wind speed at another height. This adjustment is often necessary because some equations for estimating reference crop evapotranspiration are developed for wind speeds measured at a specified height. However, wind speeds at the local weather station may be measured at a different height.

The following factor can be developed to adjust for differences in measurement elevations:

$$U_2 = U_f U_1 \qquad [2–21]$$

where:
- U_2 = estimated wind speed at height Z_2
- U_f = adjustment factor for wind speed
- U_1 = measured wind speed at height Z_1

The adjustment factor (U_f) depends on the heights of the wind speed measurement, the desired height, and the height of the crop growing at the weather station where wind speed U_1 was measured:

$$U_f = \frac{LN\left(97.56\left[\frac{Z_2}{h_c}\right] - 5.42\right)}{LN\left(97.56\left[\frac{Z_1}{h_c}\right] - 5.42\right)} \qquad [2–22]$$

where:
- U_f = adjustment factor
- Z_2 = desired height (ft)
- Z_1 = height at the weather station (ft)
- h_c = crop height (in)

Values of the adjustment factor (U_f) are summarized in table 2–4 for various values of measuring heights and weather station crop heights.

Figure 2–6 Representation of wind speeds within and above a crop canopy

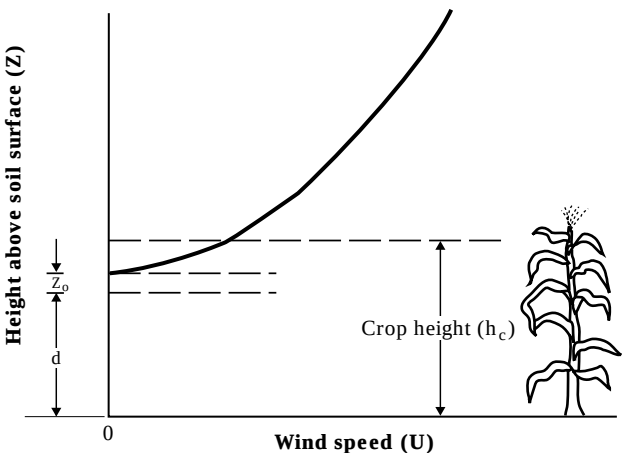


Table 2–4 Ratio of wind speeds based on measurement heights [1/]

Old wind height Z_1 (ft)	New wind height Z_2 (ft) 4	5	6	6.6	7	8	9	9.8
	Height of crop at weather station = 5 inches							
4	1.00	1.06	1.11	1.13	1.15	1.18	1.21	1.23
5	0.94	1.00	1.04	1.07	1.08	1.11	1.14	1.16
6	0.90	0.96	1.00	1.02	1.04	1.07	1.09	1.11
6.6	0.88	0.94	0.98	1.00	1.02	1.05	1.07	1.09
7	0.87	0.92	0.97	0.99	1.00	1.03	1.06	1.08
8	0.85	0.90	0.94	0.96	0.97	1.00	1.03	1.04
9	0.83	0.87	0.91	0.93	0.95	0.98	1.00	1.02
9.8	0.81	0.86	0.90	0.92	0.93	0.96	0.98	1.00
	Height of crop at weather station = 12 inches							
4	1.00	1.08	1.14	1.17	1.19	1.24	1.28	1.31
5	0.93	1.00	1.06	1.09	1.11	1.15	1.18	1.21
6	0.88	0.94	1.00	1.03	1.05	1.08	1.12	1.14
6.6	0.85	0.92	0.97	1.00	1.02	1.06	1.09	1.11
7	0.84	0.90	0.96	0.98	1.00	1.04	1.07	1.09
8	0.81	0.87	0.92	0.95	0.96	1.00	1.03	1.05
9	0.78	0.84	0.89	0.92	0.93	0.97	1.00	1.02
9.8	0.77	0.83	0.87	0.90	0.91	0.95	0.98	1.00
	Height of crop at weather station = 18 inches							
4	1.00	1.10	1.18	1.22	1.25	1.30	1.35	1.39
5	0.91	1.00	1.07	1.11	1.13	1.18	1.23	1.26
6	0.84	0.93	1.00	1.03	1.06	1.10	1.14	1.17
6.6	0.82	0.90	0.97	1.00	1.02	1.07	1.10	1.14
7	0.80	0.88	0.95	0.98	1.00	1.04	1.08	1.11
8	0.77	0.85	0.91	0.94	0.96	1.00	1.04	1.06
9	0.74	0.82	0.88	0.90	0.92	0.96	1.00	1.03
9.8	0.72	0.79	0.85	0.88	0.90	0.94	0.97	1.00
	Height of crop at weather station = 24 inches							
4	1.00	1.13	1.24	1.28	1.32	1.39	1.44	1.49
5	0.88	1.00	1.09	1.13	1.16	1.22	1.27	1.31
6	0.81	0.92	1.00	1.04	1.07	1.12	1.17	1.20
6.6	0.78	0.88	0.96	1.00	1.03	1.08	1.13	1.16
7	0.76	0.86	0.94	0.97	1.00	1.05	1.10	1.13
8	0.72	0.82	0.89	0.93	0.95	1.00	1.04	1.07
9	0.69	0.79	0.86	0.89	0.91	0.96	1.00	1.03
9.8	0.67	0.76	0.83	0.86	0.89	0.93	0.97	1.00

1/ Wind speeds are commonly measured at either 2 or 3 meters above the soil surface. These heights correspond to 6.6 and 9.8 feet, respectively.

Another value needed to compute evapotranspiration is the daytime wind speed (U_d). This speed can be estimated from the total miles of wind run per day and the ratio of the average wind speed during the day to the average wind speed at night:

$$U_d = \frac{UU_r}{12(1+U_r)} \qquad [2–23]$$

where:
U_d = daytime wind speed (mi/hr)
U = daily wind run (mi/d)
U_r = ratio of daytime to nighttime wind speeds

Doorenbos and Pruitt (1977) suggest a default value of 2 for U_r if local information is unavailable. Values of U_d for various daily wind runs and ratios of daytime to nighttime wind speed are summarized in table 2–5. An example of adjustments needed to use wind measurements is given in the example 2–3.

Example 2–3 Wind speed computations

Given: Suppose a total wind run of 300 miles per day was measured with an anemometer located 3 meters (9.8 feet) above the soil surface. In this area, the average daytime to nighttime wind speeds ratio is about 2. The grass at the weather station is maintained at 6 inches tall.

Compute:

a) The daily wind run for a height of 2 meters (6.6 feet).
b) The average daytime wind speed.

Solution:

a) The wind adjustment factor (U_f) for these conditions is determined from table 2–4 as 0.92. Then the wind run at 2 m would be computed from:

$$U_{2m} = U_f U_{3m}$$
$$U_{2m} = (0.92) \times (300 \text{ miles / day})$$
$$U_{2m} = 276 \text{ miles / day}$$

b) Using the bottom of table 2–5 gives:

$$U_d = 0.0556 \times 276$$
$$U_d = 15.3 \text{ miles / hour}$$

This compares well with the value in table 2–5 for 280 miles per day.

Table 2–5 Daytime wind speed (U_d) in miles per hour

Daily wind run (U), (mi/d)	Ratio of daytime to nighttime wind speed (U_r) 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.6	0.8	1.0	1.1	1.2	1.3	1.3	1.3
40	1.1	1.7	2.0	2.2	2.4	2.5	2.6	2.7
60	1.7	2.5	3.0	3.3	3.6	3.8	3.9	4.0
80	2.2	3.3	4.0	4.4	4.8	5.0	5.2	5.3
100	2.8	4.2	5.0	5.6	6.0	6.3	6.5	6.7
120	3.3	5.0	6.0	6.7	7.1	7.5	7.8	8.0
140	3.9	5.8	7.0	7.8	8.3	8.8	9.1	9.3
160	4.4	6.7	8.0	8.9	9.5	10.0	10.4	10.7
180	5.0	7.5	9.0	10.0	10.7	11.3	11.7	12.0
200	5.6	8.3	10.0	11.1	11.9	12.5	13.0	13.3
220	6.1	9.2	11.0	12.2	13.1	13.8	14.3	14.7
240	6.7	10.0	12.0	13.3	14.3	15.0	15.6	16.0
260	7.2	10.8	13.0	14.4	15.5	16.3	16.9	17.3
280	7.8	11.7	14.0	15.6	16.7	17.5	18.1	18.7
300	8.3	12.5	15.0	16.7	17.9	18.8	19.4	20.0
320	8.9	13.3	16.0	17.8	19.0	20.0	20.7	21.3
340	9.4	14.2	17.0	18.9	20.2	21.3	22.0	22.7
360	10.0	15.0	18.0	20.0	21.4	22.5	23.3	24.0
380	10.6	15.8	19.0	21.1	22.6	23.8	24.6	25.3
400	11.1	16.7	20.0	22.2	23.8	25.0	25.9	26.7
420	11.7	17.5	21.0	23.3	25.0	26.3	27.2	28.0
440	12.2	18.3	22.0	24.4	26.2	27.5	28.5	29.3
460	12.8	19.2	23.0	25.6	27.4	28.8	29.8	30.7
480	13.3	20.0	24.0	26.7	28.6	30.0	31.1	32.0
500	13.9	20.8	25.0	27.8	29.8	31.3	32.4	33.3
520	14.4	21.7	26.0	28.9	31.0	32.5	33.7	34.7
540	15.0	22.5	27.0	30.0	32.1	33.8	35.0	36.0
560	15.6	23.3	28.0	31.1	33.3	35.0	36.3	37.3
580	16.1	24.2	29.0	32.2	34.5	36.3	37.6	38.7
600	16.7	25.0	30.0	33.3	35.7	37.5	38.9	40.0
620	17.2	25.8	31.0	34.4	36.9	38.8	40.2	41.3
640	17.8	26.7	32.0	35.6	38.1	40.0	41.5	42.7
660	18.3	27.5	33.0	36.7	39.3	41.3	42.8	44.0
680	18.9	28.3	34.0	37.8	40.5	42.5	44.1	45.3
700	19.4	29.2	35.0	38.9	41.7	43.8	45.4	46.7
720	20.0	30.0	36.0	40.0	42.9	45.0	46.7	48.0

For daily wind runs not listed in the first column, multiply U by the factor below to get U_d:

0.0278	0.0417	0.0500	0.0556	0.0595	0.0625	0.0648	0.0667

(e) Estimating net radiation

In many locations, solar radiation provides the majority of the energy used to evaporate water. Solar radiation is so important that it currently is being measured at many locations throughout the world. In other locations, it may be necessary to estimate solar radiation from observed data. This section reviews several methods of determining solar radiation.

Ultimately, net radiation (R_n) must be predicted from observations of solar radiation (R_s). The basic method of Wright (1982) is used here to predict net radiation:

$$R_n = (1-\alpha)R_s - R_b \qquad [2–24]$$

where:
R_n = net radiation (lang/d)
α = albedo of crop and soil surface
R_s = incoming solar radiation (lang/d)
R_b = net outgoing longwave radiation (lang/d)

All radiation quantities used in the chapter are expressed in units of langleys per day, which will be abbreviated by lang/d.

At this point, it is assumed that the solar radiation (R_s) has been measured. Methods to estimate R_s are presented later in the section. To estimate net radiation, the albedo for a grass reference crop and the net outgoing longwave radiation must be determined.

The albedo (α) is the fraction of the incoming shortwave solar radiation that is reflected from the soil and crop surface back into the atmosphere. The albedo depends on the angle between the Sun's rays and a horizontal plane at the Earth's surface. This angle is called the solar altitude and varies for the day of the year, time of day, and latitude of the location. Dong, Grattan, Carroll, and Prashar (1992) developed a method to estimate hourly net radiation during the daytime for well watered grass. Their results were used to estimate the mean daytime albedo for a grass reference crop. The expression for the mean daytime albedo is based on the solar altitude when the Sun reaches the maximum height during the day, or at solar noon. The resulting expression for the mean daytime albedo is:

$$\alpha = 0.108 + 0.000939\,\theta_m + 0.257\ \mathrm{EXP}\left(-\frac{\theta_m}{57.3}\right) \qquad [2–25]$$

where:
α = the mean daytime albedo for a grass reference crop
θ_m = solar altitude at solar noon for the current day
EXP = the exponential function

The solar altitude is computed based on the relationships given by Dvoracek and Hannabas (1990):

$$\theta_m = \mathrm{SIN}^{-1}\left(\mathrm{SIN}\ \theta_d \mathrm{SIN\ Lat} + \mathrm{COS}\ \theta_d\ \mathrm{COS\ Lat}\right) \qquad [2–26]$$

and

$$\theta_d = \mathrm{SIN}^{-1}\left[0.39795\ \mathrm{COS}\left(0.98563(\mathrm{DOY}-173)\right)\right] \qquad [2–27]$$

where:
θ_m = solar altitude at solar noon (degrees)
θ_d = solar declination angle (degrees)
Lat = latitude (degrees)
DOY = the day of the year

The solar declination is the angular distance of the sun north (+) or south (–) of the equator. The declination angle is zero at the time of the vernal equinox (about March 21) and autumnal equinox (about September 23). The declination angle reaches a maximum value of 23.5° at the time of the summer solstice (about June 22).

The procedure described in equation 2–25 is not applicable when overcast conditions cause very diffuse insulation. For overcast conditions, when the ratio of $R_s/R_{so} \le 0.7$, the albedo for a grass reference crop is about 0.26.

The value of the albedo as a function of the time of year for northern latitudes is shown in figure 2–7. The albedo reaches a minimum during the summer primarily because of the angle of the Sun.

The net outgoing longwave radiation (R_b) is generally estimated based on the amount of cloud cover and the emissivity of the atmosphere. Wright (1982) predicts the net outgoing longwave radiation as:

$$R_b = \left(a\frac{R_s}{R_{so}} + b\right)R_{bo} \qquad [2–28]$$

where:

R_{so} = the amount of incident solar radiation on a clear day

R_{bo} = the net outgoing longwave radiation on a clear day

The parameters a and b in equation 2–28 depend on the amount of cloud cover: If

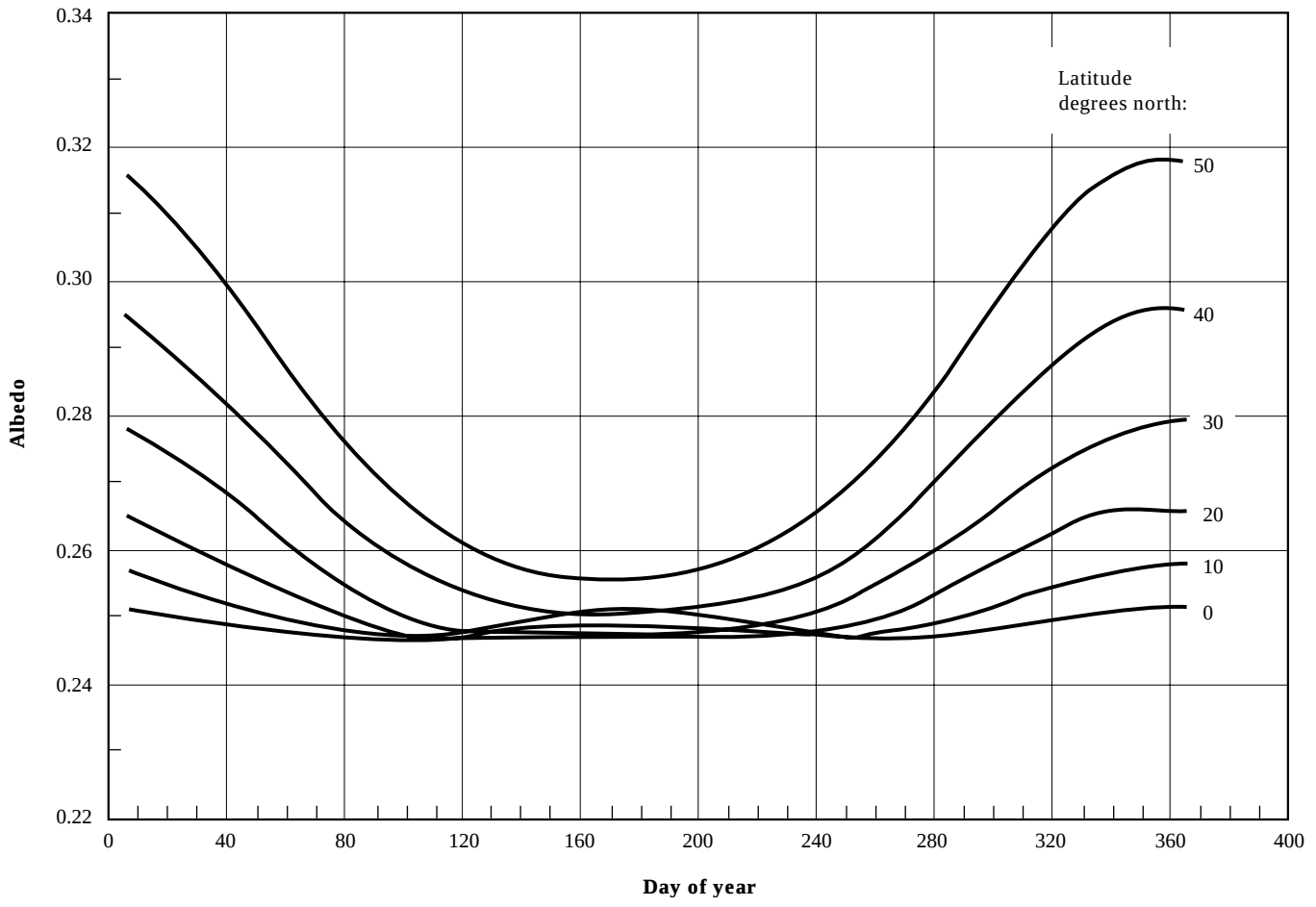
$$\frac{R_s}{R_{so}} > 0.7$$

$$a = 1.126 \text{ and } b = -0.07, \text{ and}$$

$$\text{when } \frac{R_s}{R_{so}} \leq 0.7$$

$$a = 1.017 \text{ and } b = -0.06$$

Figure 2–7 Variation of albedo during the year for selected latitudes



The amount of clear sky solar radiation (R_{so}) and the net outgoing longwave radiation (R_{bo}) on a clear day are generally predicted using empirical equations. Heermann, et al. (1985) developed an equation to predict the clear sky radiation based upon the latitude, elevation above sea level, and the time of year. An example for this function is given in figure 2–8. The equation to describe the clear sky shortwave radiation can be expressed by:

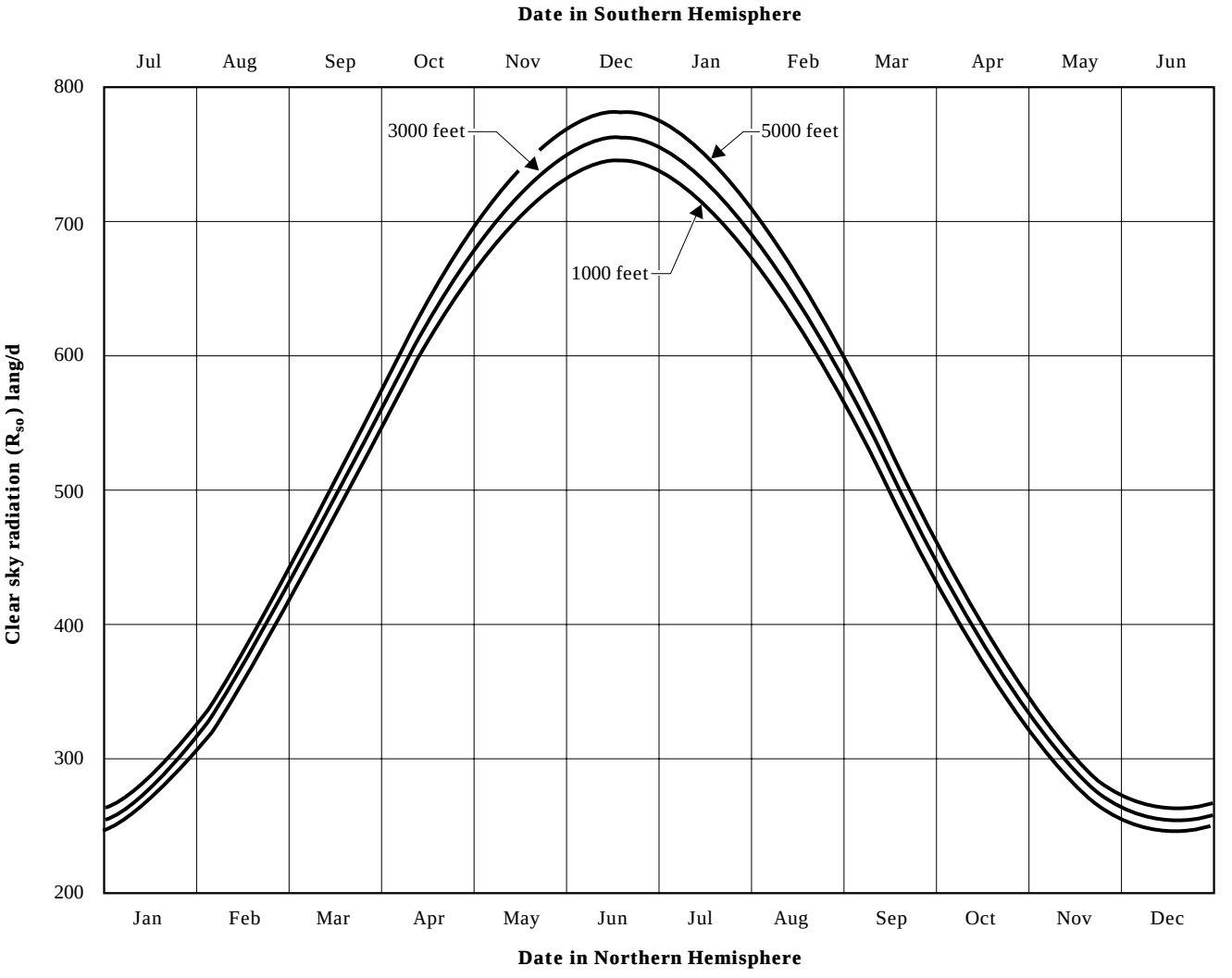
$$R_{so} = A + B\,\mathrm{COS}\left[0.9863\left(\mathrm{DOY} - 170\right)\right] \qquad [2–29]$$

where:

A = 753.6 – 6.53 Lat + 0.0057 E_{lev}
B = –7.1 + 6.40 Lat + 0.0030 E_{lev}
DOY = day of the year (1–365)
Lat = latitude (°N)
E_{lev} = elevation above sea level (ft)

The COS function is evaluated in the degrees mode.

Figure 2–8 Effect of date and elevation on clear sky radiation at 40°N latitude



Equation 2–29 is difficult to express in one table so the equation has been changed to:

$$R_{so} = R^{o}_{so} + R^{e}_{so} \qquad [2–30]$$

where:

R^{o}_{so} = clear sky radiation at sea level

R^{e}_{so} = clear sky radiation correction term for elevation

Values for R^{o}_{so} and R^{e}_{so} are summarized in tables 2–6 and 2–7. Example 2–4 illustrates how to compute clear sky radiation.

The net outgoing longwave radiation on a clear day (R_{bo}) depends on emissivity of the atmosphere (e´) and the temperature of the crop and soil. These temperatures generally are estimated and are called the temperature at the earth's surface. The general equation to describe R_{bo} is given by:

$$R_{bo} = \varepsilon' \sigma T_s^4 \qquad [2–31]$$

where:

ε' = net atmospheric emittance,

σ = Stephan-Boltzman constant, 11.71×10^{-8} lang/(day °K^4)

T_s = effective absolute temperature of the earth's surface (°K)

The effective temperature of the Earth's surface is calculated as:

$$T_s^4 = \frac{1}{2}\left[\left(\frac{5}{9}T_{max} + 255.4\right)^4 + \left(\frac{5}{9}T_{min} + 255.4\right)^4\right] \qquad [2–32]$$

where:

T_{max} = daily maximum temperature (°F)

T_{min} = daily minimum temperature (°F)

Example 2–4 Clear sky radiation (R_{so})

Compute: The clear sky radiation at the example site near Dodge City, KS, for June, July, and August.

Solution:

Elevation at Dodge City = 2,600 feet
Latitude at Dodge City = 38° N

Use interpolation to determine R^{o}_{so} for 38° N from table 2–6.

Interpolate in table 2–7 to determine R^{e}_{so} for 2,600 feet.

	R^{o}_{so} (lang/d)	R^{e}_{so} (lang/d)	R_{so} (lang/d)
June 10	738	22.5	761
July 10	726	22.1	748
August 10	653	19.7	673

Table 2–6 Clear sky radiation at sea level for various latitudes and dates

Month	Day	Degrees N latitude 0	10	20	30	40	50	60
		R^o_{so} (lang/d)						
January	1	761	633	505	378	250	123	
	10	760	636	511	386	262	137	13
	20	760	640	521	401	281	162	42
February	1	759	647	536	424	313	202	90
	10	758	654	550	446	342	238	134
	20	757	662	567	473	378	283	189
March	1	756	670	585	499	413	328	242
	10	755	679	603	527	451	375	299
	20	754	689	624	558	493	428	363
April	1	752	700	648	596	544	493	441
	10	751	709	666	624	581	539	497
	20	750	717	685	652	620	587	555
May	1	749	726	703	681	658	635	612
	10	748	732	716	700	685	669	653
	20	747	738	728	718	709	699	690
June	1	747	742	738	734	729	725	721
	10	747	745	742	740	738	736	734
	20	747	745	744	743	741	740	739
July	1	747	744	741	739	736	733	731
	10	747	742	736	731	725	720	714
	20	747	737	727	717	707	696	686
August	1	748	730	712	694	676	658	640
	10	749	724	699	673	648	623	598
	20	750	716	681	647	612	578	544
September	1	752	705	658	612	565	519	472
	10	753	696	640	584	528	471	415
	20	754	687	619	552	485	418	350
October	1	755	676	597	517	438	359	280
	10	756	667	579	490	401	313	224
	20	757	659	560	462	363	264	166
November	1	758	649	540	431	322	213	104
	10	759	643	528	412	296	180	65
	20	760	638	516	395	273	151	29
December	1	760	634	508	381	255	128	
	10	761	632	503	375	246	118	
	20	761	631	502	373	244	114	

Interpolate as needed for date and latitude.

Table 2–7 Clear sky radiation correction term for elevation

Month	Day	Elevation, feet 1000	2000	3000	4000	5000	6000	7000
		R^e_{so} (lang/d)						
January	1	2.8	5.6	8.3	11.1	13.9	16.7	19.5
	10	2.9	5.8	8.8	11.7	14.6	17.5	20.5
	20	3.2	6.3	9.5	12.6	15.8	18.9	22.1
February	1	3.5	7.1	10.6	14.2	17.7	21.2	24.8
	10	3.9	7.8	11.7	15.5	19.4	23.3	27.2
	20	4.3	8.6	13.0	17.3	21.6	25.9	30.2
March	1	4.7	9.5	14.2	19.0	23.7	28.5	33.2
	10	5.2	10.4	15.6	20.8	26.0	31.2	36.4
	20	5.7	11.4	17.1	22.9	28.6	34.3	40.0
April	1	6.3	12.7	19.0	25.3	31.6	38.0	44.3
	10	6.8	13.5	20.3	27.1	33.9	40.6	47.4
	20	7.2	14.5	21.7	28.9	36.2	43.4	50.7
May	1	7.7	15.4	23.1	30.8	38.5	46.2	53.9
	10	8.0	16.0	24.0	32.1	40.1	48.1	56.1
	20	8.3	16.6	24.9	33.2	41.5	49.9	58.2
June	1	8.6	17.1	25.7	34.2	42.8	51.3	59.9
	10	8.7	17.3	26.0	34.7	43.3	52.0	60.6
	20	8.7	17.4	26.1	34.8	43.5	52.2	60.9
July	1	8.6	17.3	25.9	34.5	43.2	51.8	60.5
	10	8.5	17.0	25.5	34.0	42.5	51.0	59.5
	20	8.3	16.6	24.8	33.1	41.4	49.7	58.0
August	1	7.9	15.8	23.7	31.7	39.6	47.5	55.4
	10	7.6	15.2	22.7	30.3	37.9	45.5	53.0
	20	7.1	14.3	21.4	28.6	35.7	42.9	50.0
September	1	6.6	13.2	19.7	26.3	32.9	39.5	46.0
	10	6.1	12.2	18.4	24.5	30.6	36.7	42.9
	20	5.6	11.2	16.8	22.4	28.0	33.7	39.3
October	1	5.0	10.1	15.1	20.2	25.2	30.3	35.3
	10	4.6	9.2	13.8	18.4	23.0	27.6	32.2
	20	4.1	8.3	12.4	16.6	20.7	24.8	29.0
November	1	3.6	7.3	10.9	14.6	18.2	21.9	25.5
	10	3.3	6.7	10.0	13.3	16.7	20.0	23.3
	20	3.1	6.1	9.2	12.2	15.3	18.3	21.4
December	1	2.8	5.7	8.5	11.3	14.2	17.0	19.8
	10	2.7	5.5	8.2	10.9	13.7	16.4	19.1
	20	2.7	5.4	8.1	10.8	13.5	16.2	18.9

Interpolate for unlisted elevations.

The atmospheric emittance depends on the amount of water vapor in the air. As the amount of water vapor increases, the emittance decreases. Wright (1982) described the emittance as:

$$\varepsilon' = a_1 - 0.044\sqrt{e_d} \qquad [2–33]$$

where:

ε' = the net atmospheric emittance

e_d = saturation vapor pressure at the mean dew point temperature (mb)

a_1 = factor to account for the change of emissivity because of day length: [2–34]

$$a_1 = 0.26 + 0.1\,\mathrm{EXP}\left\{-\left[0.0154\left(-170 + 0.986\ \mathrm{DOY}\right)\right]^2\right\}$$

EXP = exponential function

Values for a_1 are summarized for various dates in table 2–8. Values of the emittance can be computed using equation 2–33 and are summarized for various conditions in table 2–8.

The product of $'\sigma T_s^4$ in equation 2–31 represents the amount of longwave radiation emitted by an ideal surface called a black body. Computed results are summarized in table 2–9. The process to compute the outgoing longwave radiation for a clear sky is illustrated in example 2–5.

Once these values are known, the net outgoing longwave radiation (R_b) can be computed using equation 2–28. This process is illustrated in example 2–6.

The net radiation can now be calculated based upon the data for the example site as illustrated in example 2–7.

Example 2–5 Outgoing longwave radiation R_{bo}

Given: The average maximum and minimum air temperatures for June 10 at the example site are 88 °F and 61 °F, respectively, with a dew point temperature of 57 °F.

Compute: The outgoing longwave radiation for a clear sky (R_{bo}) for June.

Solution: Use equation 2–11 to compute the saturated vapor pressure at the dew point temperature, e_d = 15.9 mb. From table 2–8 or equation 2–33 and 2–34, the atmospheric emittance (ε') is 0.18.

From table 2–9, the black body radiation ($'\sigma T_s^4$) is 910 lang/d.

Then:

$$R_{bo} = \varepsilon'\sigma T_s^4 = 0.18 \times 910\ \mathrm{lang/d} = 164\ \mathrm{lang/d}$$

Example 2–6 Outgoing longwave radiation (R_b) for a clear sky

Compute: The net outgoing longwave radiation for the example site for June 10 where R_s = 650 lang/d.

Solution:

$$R_b = \left(a\frac{R_s}{R_{so}} + b\right)R_{bo}$$

From example 2–4, R_{so} = 761 lang/d
From example 2–5, R_{bo} = 164 lang/d
The ratio of R_s/R_{so} = 0.85
Thus a = 1.126 and b = –0.07.
Therefore, R_b = (1.126 x 0.85 – 0.07) 164 lang/d
R_b = 145 lang/d

Example 2–7 Net outgoing longwave radiation (R_n)

Compute: The net radiation for the example site on June 10.

Solution: From equation 2–24:

$$R_n = (1-\alpha)R_s - R_b$$

Since the ratio of R_s/R_{so} > 0.70, use equations 2–25 through 2–27 to find the albedo.

June 10 is the 161st day of the year, so DOY = 161.
From equation 2–27, the solar declination θ_d = 22.9°.
The latitude at the site is 37°46' or 37.8°.
Using the solar declination and latitude, the solar altitude is given by:

$$\theta_m = \mathrm{SIN}^{-1}\left[\mathrm{SIN}(22.9)\times\mathrm{SIN}(37.8)+\mathrm{COS}(22.9)\mathrm{COS}(37.8)\right] = 75^\circ$$

The albedo is then computed as:

$$\alpha = 0.108 + 0.000939\times(75) + 0.257\times\mathrm{EXP}\left(\frac{-75}{57.3}\right)$$

$$\alpha = 0.25$$

From example 2–6, R_b = 145 lang/d, and R_s = 650 lang/d for the example site.
Thus, the net radiation (R_n) is:

$$R_n = (1-0.25)\times 650 - 145$$

$$R_n = 343 \text{ lang / d}$$

Table 2–8 Values of the a_1 parameter and the atmospheric emittance (ε′)

Month	Day	a_1	Saturated vapor pressure at dew point temperature, mb							
			5	10	15	20	25	30	35	40
January	1	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	10	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	20	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
February	1	0.261	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	10	0.261	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	20	0.262	0.16	0.12	0.09	0.07	0.04	0.02	0.00	
March	1	0.264	0.17	0.12	0.09	0.07	0.04	0.02	0.00	
	10	0.267	0.17	0.13	0.10	0.07	0.05	0.03	0.01	
	20	0.271	0.17	0.13	0.10	0.07	0.05	0.03	0.01	
April	1	0.277	0.18	0.14	0.11	0.08	0.06	0.04	0.02	0.00
	10	0.285	0.19	0.15	0.11	0.09	0.06	0.04	0.02	0.01
	20	0.294	0.20	0.16	0.12	0.10	0.07	0.05	0.03	0.02
May	1	0.308	0.21	0.17	0.14	0.11	0.09	0.07	0.05	0.03
	10	0.319	0.22	0.18	0.15	0.12	0.10	0.08	0.06	0.04
	20	0.332	0.23	0.19	0.16	0.14	0.11	0.09	0.07	0.05
June	1	0.345	0.25	0.21	0.17	0.15	0.13	0.10	0.08	0.07
	10	0.353	0.25	0.21	0.18	0.16	0.13	0.11	0.09	0.08
	20	0.359	0.26	0.22	0.19	0.16	0.14	0.12	0.10	0.08
July	1	0.360	0.26	0.22	0.19	0.16	0.14	0.12	0.10	0.08
	10	0.356	0.26	0.22	0.19	0.16	0.14	0.12	0.10	0.08
	20	0.348	0.25	0.21	0.18	0.15	0.13	0.11	0.09	0.07
August	1	0.336	0.24	0.20	0.17	0.14	0.12	0.10	0.08	0.06
	10	0.324	0.23	0.19	0.15	0.13	0.10	0.08	0.06	0.05
	20	0.311	0.21	0.17	0.14	0.11	0.09	0.07	0.05	0.03
September	1	0.298	0.20	0.16	0.13	0.10	0.08	0.06	0.04	0.02
	10	0.288	0.19	0.15	0.12	0.09	0.07	0.05	0.03	0.01
	20	0.280	0.18	0.14	0.11	0.08	0.06	0.04	0.02	0.00
October	1	0.272	0.17	0.13	0.10	0.08	0.05	0.03	0.01	
	10	0.268	0.17	0.13	0.10	0.07	0.05	0.03	0.01	
	20	0.265	0.17	0.13	0.09	0.07	0.04	0.02	0.00	
November	1	0.263	0.16	0.12	0.09	0.07	0.04	0.02	0.00	
	10	0.262	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	20	0.261	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
December	1	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	10	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	
	20	0.260	0.16	0.12	0.09	0.06	0.04	0.02	0.00	

Table 2–9 Emittance of longwave radiation by a perfect black body (σT_s^4), lang/d

Max. temp. (°F)	Minimum daily temperature, °F																			
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
10	520	532	543																	
15	532	543	555	566																
20	544	555	567	578	591															
25	557	568	579	591	603	616														
30	570	581	592	604	616	629	641													
35	583	594	605	617	629	642	655	668												
40	597	608	619	631	643	656	668	682	695											
45	611	622	633	645	657	670	683	696	710	724										
50	625	636	648	660	672	684	697	710	724	738	753									
55	640	651	663	675	687	699	712	725	739	753	768	783								
60	656	667	678	690	702	715	728	741	755	769	783	798	814							
65	672	683	694	706	718	731	743	757	770	785	799	814	830	845						
70	688	699	710	722	734	747	760	773	787	801	815	830	846	862	878					
75	705	716	727	739	751	764	777	790	804	818	832	847	863	879	895	912				
80	722	733	745	756	768	781	794	807	821	835	850	865	880	896	912	929	946			
85	740	751	762	774	786	799	812	825	839	853	867	882	898	914	930	947	964	982		
90	758	769	781	792	805	817	830	843	857	871	886	901	916	932	948	965	982	1000	1018	
95	777	788	799	811	823	836	849	862	876	890	904	919	935	951	967	984	1001	1019	1037	1056
100	796	807	819	830	843	855	868	881	895	909	924	939	954	970	986	1003	1020	1038	1057	1075
105	816	827	839	850	862	875	888	901	915	929	944	959	974	990	1006	1023	1040	1058	1076	1095
110	837	848	859	871	883	895	908	921	935	949	964	979	994	1010	1027	1043	1061	1078	1097	1115
115	857	868	880	892	904	916	929	942	956	970	985	1000	1015	1031	1047	1064	1082	1099	1118	1136
120	879	890	901	913	925	938	951	964	978	992	1006	1021	1037	1053	1069	1086	1103	1121	1139	1158

(f) Estimating solar radiation

In some locations, solar radiation is not measured, but can be estimated based upon extraterrestrial radiation (R_a). Extraterrestrial radiation represents the radiation intensity above the Earth's atmosphere and is unaffected by cloud cover. Thus, extraterrestrial radiation depends only on the time of year and the latitude (fig. 2–9). Values for the extraterrestrial radiation are tabulated for various dates and latitudes in table 2–10.

Doorenbos and Pruitt (1977) recommended using the following expression to relate solar to extraterrestrial radiation:

$$R_s = \left[0.25 + 0.50\frac{n}{N}\right]R_a \qquad [2–35]$$

where:

$\frac{n}{N}$ = the ratio between actual bright sunshine hours (n) and maximum possible sunshine hours (N) per day.

Figure 2–9 Extraterrestrial radiation as a function of time for various latitudes

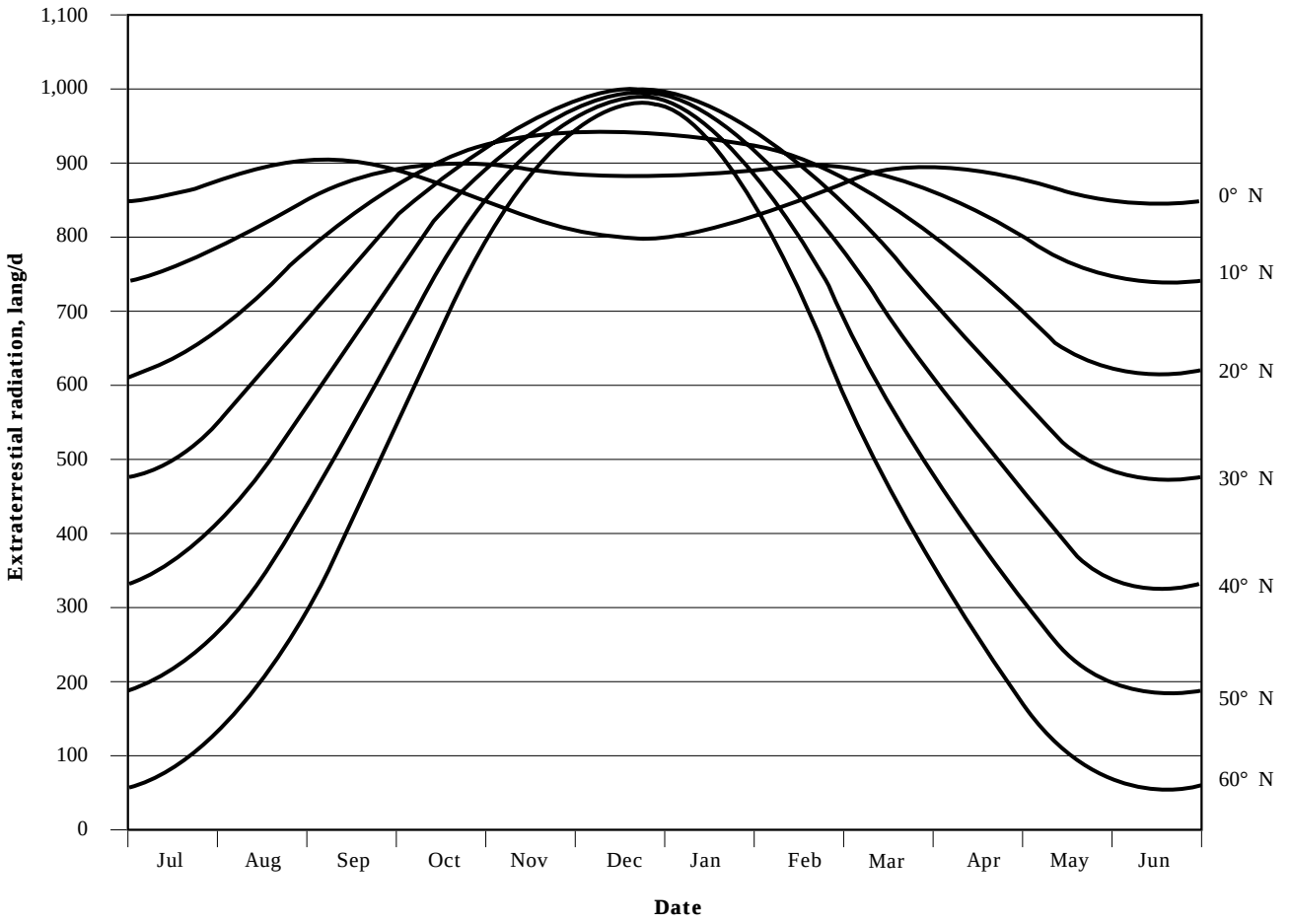


Table 2–10 Extraterrestrial radiation (R_a), lang/d

Date	Degrees North Latitude						
	0	10	20	30	40	50	60
January 1	854	744	617	477	330	184	55
January 10	859	754	629	491	345	199	67
January 20	868	769	650	516	372	226	89
February 1	880	793	683	557	418	272	130
February 10	890	812	713	594	459	316	171
February 20	898	835	748	639	512	373	227
March 1	904	856	783	687	570	438	294
March 10	906	873	814	730	625	501	362
March 20	904	888	846	778	686	573	443
April 1	895	900	878	830	757	661	545
April 10	884	905	898	865	806	724	622
April 20	870	906	916	899	856	790	705
May 1	852	903	929	929	904	855	789
May 10	837	899	936	948	936	901	850
May 20	822	893	941	965	964	942	907
June 1	808	887	944	977	987	978	957
June10	800	884	945	982	997	993	980
June 20	797	882	944	984	1001	998	988
July 1	799	882	942	980	995	990	976
July 10	805	884	940	973	983	973	952
July 20	815	887	936	961	962	942	909
August 1	831	892	929	940	927	892	841
August 10	845	895	920	919	894	845	779
August 20	860	897	907	891	850	786	702
September 1	877	894	885	850	790	706	603
September 10	886	889	865	814	740	643	526
September 20	893	879	837	771	681	570	442
October 1	896	862	803	720	615	491	354
October 10	894	846	773	677	561	430	288
October 20	889	826	738	630	505	367	222
November 1	880	800	698	578	443	300	157
November 10	872	782	671	544	404	259	119
November 20	863	764	645	512	369	223	87
December 1	855	749	625	487	341	196	65
December 10	851	742	614	474	328	182	54
December 20	851	739	611	470	323	178	50
December 31	854	744	617	477	330	184	55

The ratio n/N can be estimated and is available for many locations for average conditions (USDC 1977). Average ratios can be very useful in designing irrigation systems, but are more difficult to determine for daily calculations for irrigation scheduling. The solar radiation should be measured directly for scheduling or other short-term estimates. Example 2–8 illustrates the estimation of R_s.

A flow chart (fig. 2–10) has been prepared to assist with computing radiation terms. This chart assumes that either R_s or the ratio n/N is known.

(g) Soil heat flux

The soil is capable of absorbing, emitting, and storing energy. Some energy available for evapotranspiration could be used to heat the soil. Conversely, if the soil is warmer than the crop, the soil could provide some energy for evapotranspiration. The amount of energy entering or leaving the soil, called the soil heat flux, is denoted by the symbol G. If the algebraic value of G is positive, the soil is absorbing energy. If G is less than zero, the soil is providing energy for evapotranspiration.

The average daily amount of soil heat flux over a 10 to 30 day period is usually small. The value of G generally becomes more important for daily calculations and for long-term estimates. Wright (1982) presented the following method of computing the daily soil heat flux:

$$G = c_s\left(T_a - T_p\right) \qquad [2–36]$$

where:

G = soil heat flux (lang/d)
c_s = an empirical specific heat coefficient for the soil (lang/°F/d)
T_a = average air temperature for the current day, (°F)
T_p = mean air temperature for the preceding three days (°F)

Wright (1982) used a value of 5 langleys per degree Fahrenheit per day for c_s for an alfalfa crop at Kimberly, Idaho. The value of c_s varies for grass grown on other soils and in other locations. Unfortunately, other values of c_s are not readily available, and the value from Wright should be used as an initial approximation. Computation of the soil heat flux with this method is illustrated in example 2–9.

For monthly or longer ET estimates, Jensen, et al. (1990) presented a method that assumes that the soil temperature at a depth of 6.6 feet is approximately the average temperature for the previous time period. Their method is given by:

$$G_i = 55.7\,\frac{\left(T_{i+1} - T_{i-1}\right)}{\Delta t} \qquad [2–37]$$

where:

G_i = soil heat flux in lang/d for period i
T = average air temperature in °F in time period i+1 and i–1
Δt = time interval for period i in days

Example 2–8 R_s estimate

Estimate: The average amount of solar radiation in June for the example site.

Solution: The ratio of (n/N) for June is 0.74 (from table 2–3)

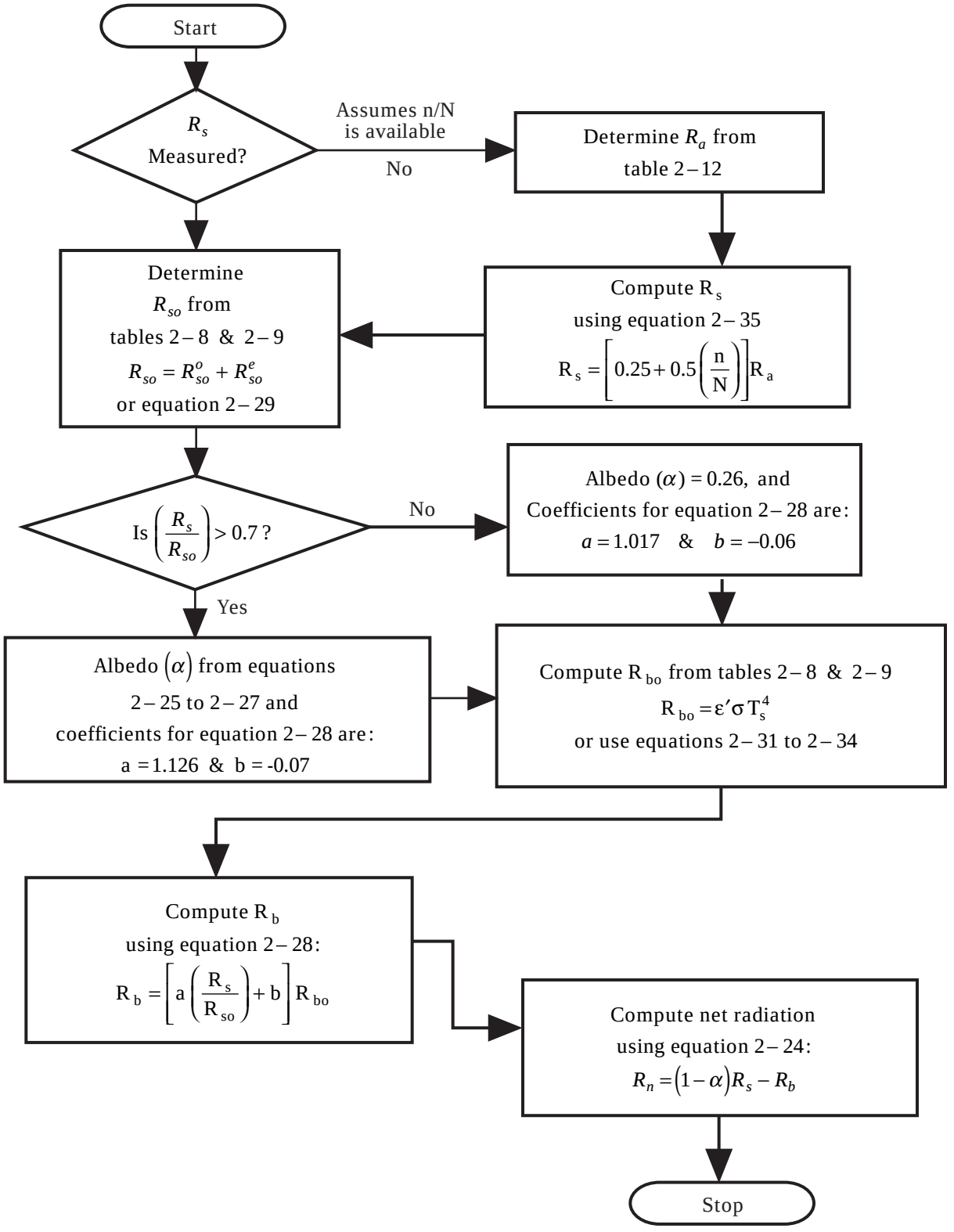
For the example site, the extraterrestrial radiation is 994 lang/d for June 10 (from table 2–10).

The solar radiation would be about:

$$R_s = \left[0.25 + \left(0.50 \times 0.74\right)\right]994 = 616 \text{ lang / d}$$

From this point, the net radiation could be estimated.

Figure 2–10 Flow chart for computing net radiation



It should be emphasized that equation 2–37 is not applicable for daily calculations. Example 2–10 illustrates calculation for the monthly soil heat flux.

In summary, to calculate the soil heat flux, equation 2–36 should be used for daily calculations. For time periods from 10 to 30 days, the soil heat flux can generally be ignored. For monthly or longer periods, equation 2–37 should be used.

Example 2–9 Daily soil heat flux

Compute: The soil heat flux for June 10 for the following air temperature data:

Date	Daily air temperatures, °F Maximum	Minimum
June 7	80	60
June 8	85	62
June 9	72	52
June 10	74	58

Solution: Compute the average temperature as the mean of the daily maximum and minimum temperature:

Date	Average temperature, °F
June 7	70
June 8	73.5
June 9	62
June 10	66

From these data,

$$T_a = 66°F \text{ and}$$

$$T_p = \frac{(70 + 73.5 + 62)}{3}$$

$$T_p = 68.5°F$$

Then the soil heat flux is:

$$G = c_s(T_a - T_p)$$

$$G = 5 \text{ lang} / °F / d(66 - 68.5)°F$$

$$G = -13 \text{ lang} / d$$

Since the average temperature has been warmer than today, the soil is warm and provides energy to evaporate water.

(h) Weather stations

Evapotranspiration predictions are only as accurate and representative as the climatic data. The siting, maintenance, and management of the weather station are critical. Procedures should be developed to ensure that the highest quality of data is maintained. A calibration and maintenance schedule should be maintained to ensure quality and to provide records to increase user confidence in the climatic data.

Climatic data must sometimes be used from stations located some distance away from the area under study. This is permissible when weather is similar over large areas. Where the climate changes rapidly over short distances, the user must be very careful to ensure that the available climatic data is representative. In some cases, adjustment of climatic data is necessary if the weather station does not represent the irrigated area. An example is data from an airport. The airport is generally surrounded by an urban area that has a different climate than an irrigated area.

Other instances of rapid climatic changes are arid areas inland from large lakes, interior mountain valleys, and areas where an air mass is forced upward by mountain ranges. When the weather changes quickly with distance from a land or water surface, evapotranspiration may change markedly (fig. 2–11).

Studies have shown that air over irrigated areas may be 4 to 10 °F lower than over adjacent nonirrigated areas (Allen, et al. 1983 and Burman, et al. 1975). Higher relative humidities and smaller vapor pressure deficits were also measured. The differences in air temperature between irrigated and nonirrigated areas are related to the extensiveness and aridity of the surrounding area and the size of the irrigated area.

Climatic data used to design irrigation projects are often collected before irrigation development. The weather stations used to supply these data are often located in rainfed or uncultivated areas, or even at airports. Irrigated fields have different micro-climates than these stations, and ET may not be equal to predicted values when using these data. This problem is most severe in arid, windy climates.

Example 2–10 Monthly soil heat flux

Calculate: The expected soil heat flux at the example site for June.

Solution: The monthly temperature data are:

Month	Average air temperature, °F
(i–1) May	64.0
(i) June	74.5
(i+1) July	80.0

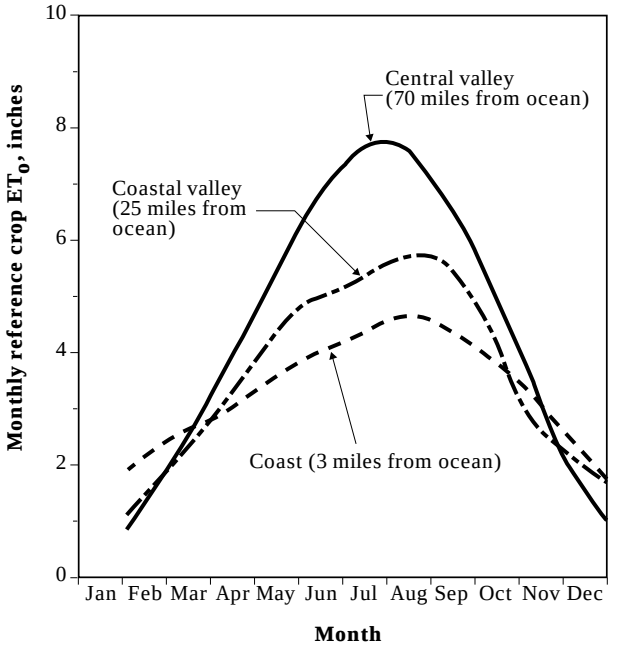
The time from the middle of May until the middle of July is about 60 days. Thus,

$$G = 55.7\frac{(80-64)}{60} = 15 \text{ lang / d}$$

Since G>0, the soil is heated during June, which requires energy that could have been used for ET.

In arid and semi-arid climates, irrigated fields surrounded by dry fallow areas are subject to advection. Air masses moving into the irrigated area give up heat as they move over the area. This results in a *clothesline effect* at the upwind edge and an *oasis effect* inside the irrigated field. With warm, dry winds, appreciably higher evapotranspiration rates can be expected at the upwind edge of the field. With distance, the air becomes cooler and more humid. Thus, the *clothesline effect* becomes negligible with distance from the border. These effects may extend between 300 and 1,200 feet in hot, dry climates where the wind speed is more than 10 miles per hour. Because of the *clothesline effect*, results of irrigation trials from small fields located in dry surroundings may indicate up to double the evapotranspiration rate of large areas.

Figure 2–11 Changes in ET_o with distance from the ocean for three locations in California (adapted from Doorenbos and Pruitt 1977)



Because of the *oasis effect*, evapotranspiration will be higher in fields surrounded by dry fallow land than in fields surrounded by extensive vegetated area. However, air temperature is generally lower and humidity higher inside the large irrigated area than that outside the area. Where evapotranspiration is predicted using climatic data collected outside or before irrigation development in semi-arid and arid areas, evapotranspiration could be overpredicted by 5 to 15 percent for fields of 10 to 50 acres and 10 to 25 percent for large projects when nearly all the area is later planted to irrigated crops. The main cause of overprediction is the distribution of fallow and cropped fields. The air above a fallow field is heated before moving to the next field. This is shown in figure 2–12 for pan evaporation across irrigated cotton and fallow fields.

Where climatic data collected from another region or before irrigation development are used, a correction factor is needed to obtain evapotranspiration data for irrigated fields of different sizes that are surrounded by dry fallow and in arid, hot areas that have moderate wind. Doorenbos and Pruitt (1977) presented the adjustment factor shown in figure 2–13. They caution that the correction factor should not be used for very small fields (<0.1 acres) because the adjustment could be very large and crop damage could result if it was incorrect.

Figure 2–12 Effect of advection on the evaporation rate from an evaporation pan (adapted from Doorenbos and Pruitt 1977)

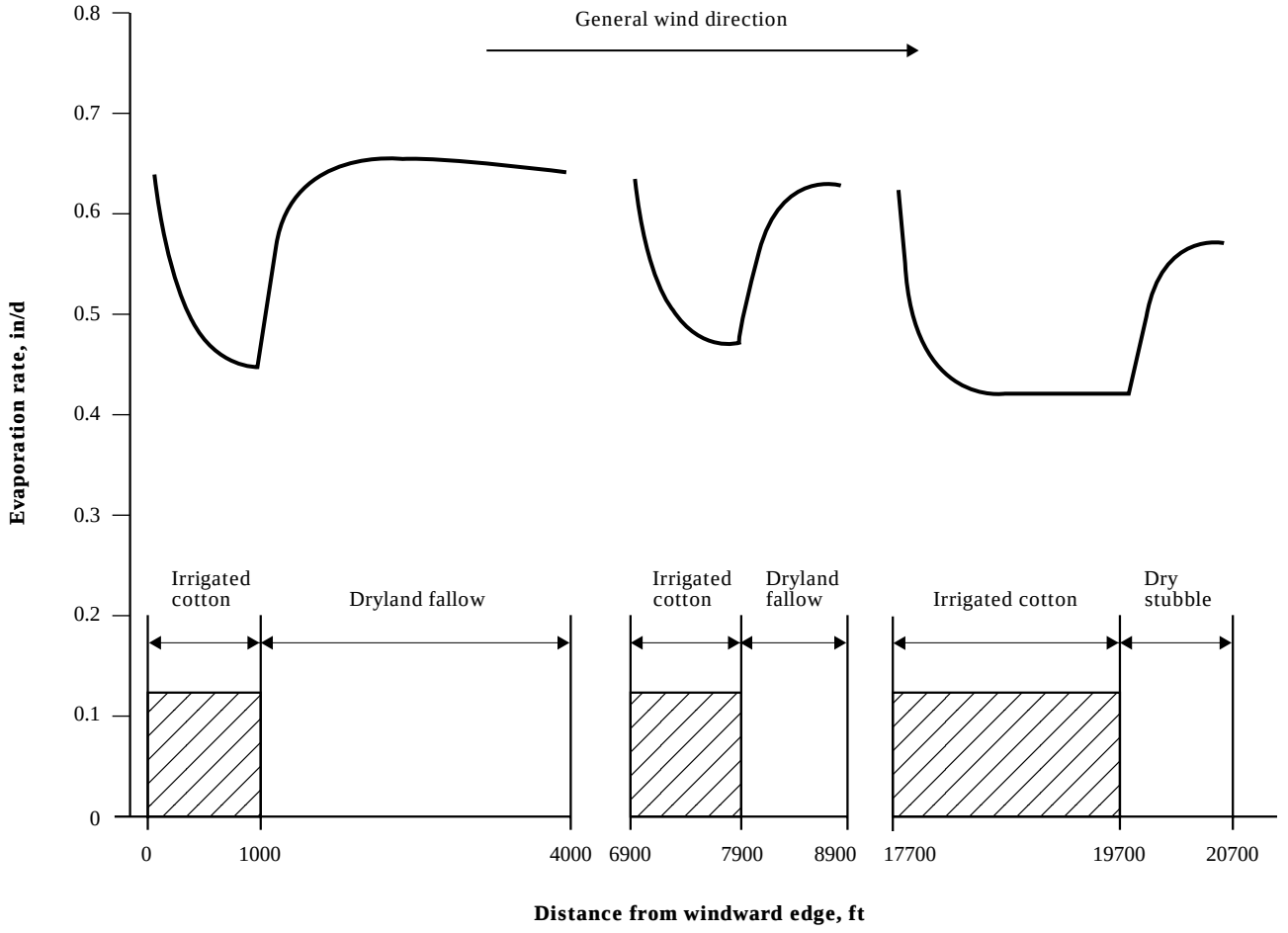
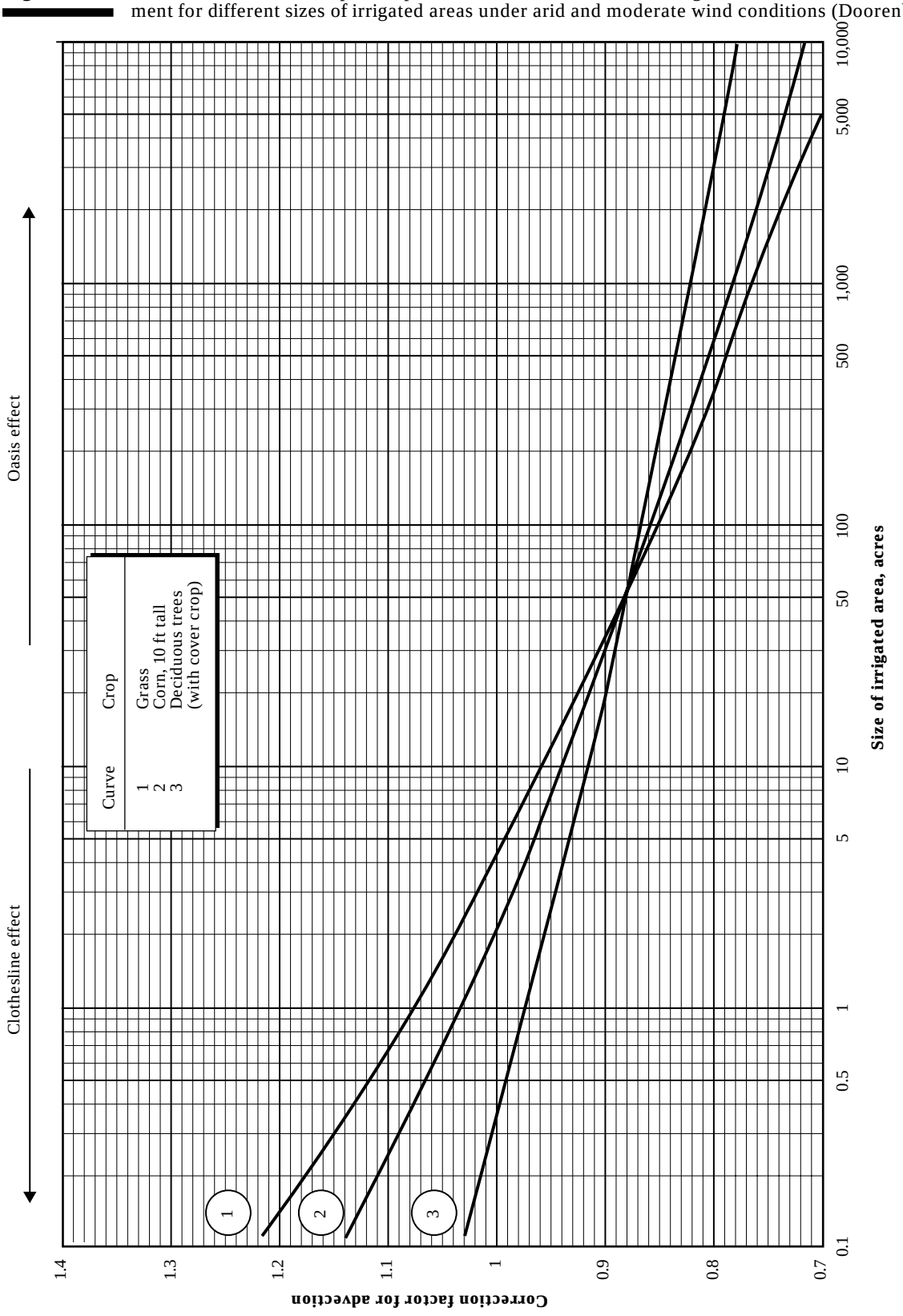


Figure 2–13 Correction factor for evapotranspiration because of advection using data outside or before irrigation development for different sizes of irrigated areas under arid and moderate wind conditions (Doorenbos and Pruitt 1977)



623.0203 Reference crop evapotranspiration

In this handbook, the reference crop is considered to be a clipped, well watered and healthy grass that is 3 to 6 inches tall. Calculation procedures assume that salinity does not affect the rate of evapotranspiration. The reference crop evapotranspiration is denoted ET_o and is generally expressed as a depth of water use per day (in/d). The ET_o represents a hypothetical crop for some locations as it may not be possible to grow such a grass throughout a season in all areas. However, ET_o can be computed as a reference for estimating actual crop evapotranspiration (ET_c) in such areas.

Various methods have been developed to compute reference crop evapotranspiration. Four methods are presented in this handbook. The most accurate, and complex, method is the Penman-Monteith method as presented by Allen (1986). Radiation and advection are both considered in the method. The Penman-Monteith method requires climatic data for air temperature and humidity, wind speed, and solar radiation. If accurate climatic data are available the method can be used for daily computation of ET_o values.

The second method is the radiation method as presented by Doorenbos and Pruitt (1977). This method requires solar radiation and air temperature data to compute evapotranspiration for the grass reference crop. Where accurate data are available, the radiation method can be confidently applied to compute average ET_o values for 5-day periods. The radiation method is not as dependable as the Penman-Monteith method when computing ET_o for a specific day.

The third method is the temperature method based on the FAO-Blaney-Criddle method developed by Doorenbos and Pruitt (1977). This method is based on actual air temperature data and long-term average conditions for relative humidity, solar radiation, and wind velocity. It has been shown to provide accurate estimates of average ET_o for 5-day periods. Like the radiation method, the temperature method is less precise than the Penman-Monteith method for estimating ET_o for only 1 day.

The final method relates ET_o to the rate of evaporation from a Class A evaporation pan. The evaporation pan method is based on procedures by Doorenbos and Pruitt (1977) to adjust the method to local humidity, wind, and fetch conditions. Because of the energy storage by evaporation pans, this method is recommended for measuring the average ET_o over 10-day periods or longer. Details on each method are presented later in this section. Details of the SCS Blaney-Criddle method as in Technical Release Number 21 are given in the appendix.

(a) Selection and application of reference crop ET method

Selection of the proper method of computing reference crop evapotranspiration depends on:

- Type, accuracy, and duration of available climatic data.
- Natural pattern of evapotranspiration during the year.
- Intended use of the evapotranspiration estimates.

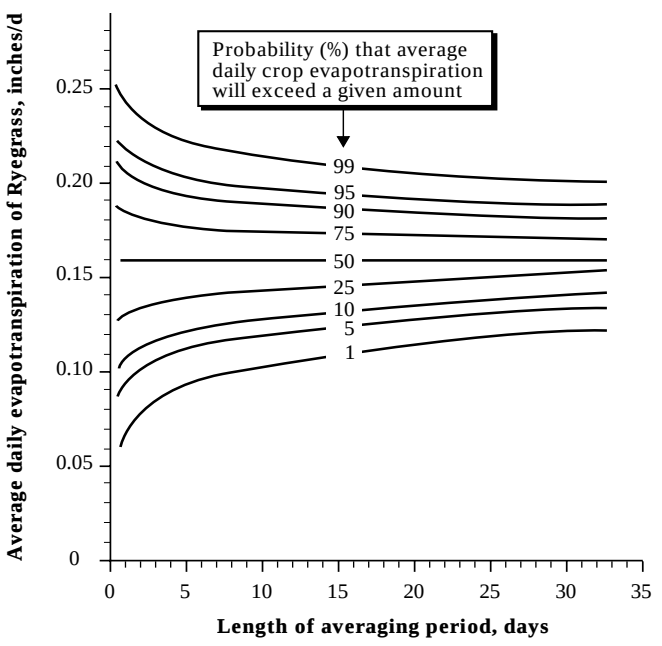
The type, quality, and length of record of climatic data greatly affect the selection of an ET_o method. Some irrigation management applications require real-time data while design and water right considerations require an assessment of historical water use patterns. Thus, the length of time that various types of data are available may dictate the type of method to use in estimating ET_o. In many locations air temperature has been recorded for long periods. Wind speed, relative humidity, and solar radiation data are less available and are more difficult to measure, causing these data to be less reliable. Thus, some locations may require use of the temperature based ET_o method while at other locations, other methods would be more appropriate. The available climatic data should be compiled and evaluated before beginning any computation. The usable methods can be identified once data quality has been determined.

The natural pattern of crop water use can affect the selection of an ET_o method. Crop evapotranspiration varies from day to day because of fluctuating climatic conditions and plant growth. The variation can be large in some climates. The daily crop evapotranspiration can be averaged over a period, such as 5 days.

This provides the average daily crop evapotranspiration for that period. The average daily crop evapotranspiration for each 5-day period of the summer could be computed for a series of years, producing a set of 5-day average daily crop evapotranspiration values. Of course, the 5-day average daily crop evapotranspiration data will vary among the sets.

An example of the variation of average daily evapotranspiration for ryegrass for different lengths of the averaging period is given in figure 2–14. The probability shown in this figure represents the chances of the average daily evapotranspiration being less than a given amount of evapotranspiration. For example, the average daily evapotranspiration for a 5-day period will be less than 0.225 inches per day for 99 percent of the values in the set of 5-day averages. If we assume that the future will resemble the past, we can expect the 5-day average evapotranspiration for ryegrass at this location to be less than 0.225 inches per day 99 percent of the time in the future.

Figure 2–14 Variation of the average daily ET_c as affected by the length of the averaging period (adapted from Doorenbos and Pruitt 1977)



Averaging dampens out the fluctuation of daily evapotranspiration data and decreases the range of average daily evapotranspiration. Therefore, the range of values for the 5-day average daily evapotranspiration is smaller than that of the daily values. This is illustrated in figure 2–14. Consider the 5-day average daily evapotranspiration for the 1 percent and 99 percent probabilities. The 5-day average daily evapotranspiration is smaller than 0.225 inches per day 99 percent of the time and smaller than 0.090 inches per day 1 percent of the time. Therefore, the 5-day average is between 0.09 and 0.225 inches per day 98 percent of the time. Compare this to when the data are averaged over 10 days. The 10-day average is between 0.10 and 0.215 inches per day 98 percent of the time.

Errors in daily estimates of reference crop evapotranspiration also tend to balance out when averaging over a period. On some days, the errors associated with either the climatic data or with the prediction method cause ET_o estimates to be excessive. On other days the method might underpredict ET_o. These errors compensate during the period, thus the accuracy of the ET_o estimate generally improves with longer computational periods (Jensen and Wright 1978).

The combined processes of less natural variation in average evapotranspiration for long periods and the error compensation within a period for ET_o predictions cause the magnitude of potential errors in ET_o estimates to decrease with the length of the computation period. Thus, less precise ET_o methods may provide adequate accuracy for long-term estimates. However, complex equations are required for short-term (daily) estimates.

Studies have shown that the Penman-Monteith method is more reliable for any length period than methods that use less climatic data (Jensen, et al. 1990). The method works well for daily calculations and for estimating monthly or seasonal water needs. If adequate data are available or can be estimated, the Penman-Monteith equation should be considered.

The radiation method and the temperature (FAO Blaney-Criddle) method are less precise than the Penman-Monteith method. These methods are acceptable for predicting the average daily water use for a period of days. However, they can produce significant errors for an individual day. Thus, these methods are recommended for calculating average ET_o for periods of 5 days or more.

The evaporation pan method is less reliable for short-term estimates than other ET_o methods and is recommended for periods of 10 days or longer. Evaporation pans can be accurate if well maintained and properly located. If the pan has a history of proper use, 10-day periods can be used. Poorly maintained pans and inappropriate siting can lead to severely biased data. If little previous history is available for a pan, caution should be exercised even for computing ET_o for longer periods.

The purpose for computing ET_o may determine the calculation method. Three examples will illustrate the variation in ET_o needs. Irrigation scheduling requires local real-time data. Irrigation system design considers a historical record to evaluate the expected maximum capacity for water supply and delivery systems. Reservoir design or water right determination may only require monthly water use estimates.

Daily ET_o estimates are not necessary for some irrigation scheduling applications. If a field is irrigated every 10 days, scheduling using the radiation or temperature based method, or an evaporation pan, may produce essentially the same schedule as that using the Penman-Monteith method. If high-value, shallow-rooted crops are grown on coarse textured soils, daily ET_o estimates may be necessary for accurate scheduling. In such cases the Penman-Monteith method would be best suited.

The selection of an ET_o method for designing an irrigation system depends on the required irrigation frequency. If crops are irrigated frequently because of a shallow root zone, coarse textured soils, or maintenance of large soil-water depletions, the required water supply rate will be larger than that for infrequent irrigation. Results in figure 2–14 illustrate this concept. To design a system you might want to meet the average daily evapotranspiration at least 90 percent of the time. If you irrigated daily, the ET_o for design would be 0.21 inches per day in figure 2–14. The design ET_o drops to 0.195 inches per day for a 5-day irrigation frequency and to 0.190 inches per day for a 10-day period (fig. 2–14). The Penman-Monteith method is needed to adequately design for the daily irrigation frequency. Either the radiation method, the temperature method, or the Penman-Monteith method will suffice for the 5- or 10-day irrigation frequency. For design, climatic data must be available for a number of years to develop the probabilities as shown in figure 2–14. A less precise ET_o method with a longer history may be preferable to a precise method where a limited length of climatic data are available.

To design and operate a reservoir, or to establish water rights, the short-term estimate of ET_o is less valuable than the monthly or annual water use pattern. Often these uses require consideration of several crops and numerous fields where exact information is not available for each parcel. Thus, average ET_o values for biweekly, monthly, or annual periods may be adequate. For these applications, all the ET_o methods are acceptable, and the quality of the available climatic or evaporation pan data may be the deciding factor.

(b) Penman-Monteith method

Jensen, et al. (1990) compared 20 methods of computing ET_o for arid and humid locations. They found that the Penman-Monteith method as modified by Allen (1986) was the most accurate for either environment. Because of its accuracy, the Penman-Monteith method is recommended when air temperature, relative humidity, wind speed, and solar radiation data are available or can be reliably estimated. The method can also be adjusted to the physical features of the local weather station.

The Penman-Monteith method is given in equation 2–38.

$$ET_o = \left(\frac{1}{\lambda}\right)\left[\left(\frac{\Delta}{\Delta+\gamma^*}\right)(R_n - G) + \left(\frac{\gamma}{\Delta+\gamma^*}\right)\left(0.622\frac{K_1\lambda\rho}{BP}\right)\frac{(e_z^\circ - e_z)}{r_a}\right] \qquad [2–38]$$

where:

ET_o = the evapotranspiration rate for a grass reference crop (in/d)
λ = heat of vaporization of water (lang/in) (equation 2–19)
R_n = net radiation (lang/d)
G = soil heat flux (lang/d)
Δ = slope of the vapor pressure curve (mb/°F) (calculated by equation 2–16)
γ = psychrometric constant (mb/°F) (calculated by equation 2–18),
ρ = density of air (lb/ft$^{3)}$
BP = mean barometric pressure (mb)
e_z^o = average saturated vapor pressure (mb) (calculated by equation 2–14)
e_z = actual vapor pressure (mb) (calculated by equation 2–15)

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \qquad (2–39)$$

where:

r_c = surface resistance to vapor transport (d/mi)
r_a = aerodynamic resistance to sensible heat and vapor transfer (d/mi)

The variables used to describe the aerodynamic resistance (r_a) are illustrated in figure 2–15. The aerodynamic resistance in units of days per mile is given by:

$$r_a = \frac{LN\left[\frac{(Z_w - d)}{Z_{om}}\right] \times LN\left[\frac{(Z_p - d)}{Z_{ov}}\right]}{0.168\ U_z} \qquad [2–40]$$

where:

LN = natural logarithm function
Z_w = the height of wind speed measurement (ft)
Z_p = the height of the humidity (psychrometer) and temperature measurements (ft)
U_z = the daily wind run at height Z_w (mi/d)
d = the displacement height for the crop (ft)
Z_{om} = the roughness length of momentum transfer (ft)
Z_{ov} = the roughness length of vapor transfer (ft)

The value of ($0.622\ K_1\ \lambda\rho/BP$) has units of langleys per mile per millibar and depends on the air temperature:

$$0.622K_1 \frac{\lambda\rho}{BP} = (82 - 0.186T) \qquad [2–41]$$

where:

K_1 = the dimension coefficient to ensure both terms have the same units
T = the air temperature (°F)

Values for ($0.622\ K_1\ \lambda\rho/BP$), Δ, λ, and γ as a function of temperature are listed in table 2–11.

Figure 2–15 Definition sketch for variables used to define the aerodynamic resistance

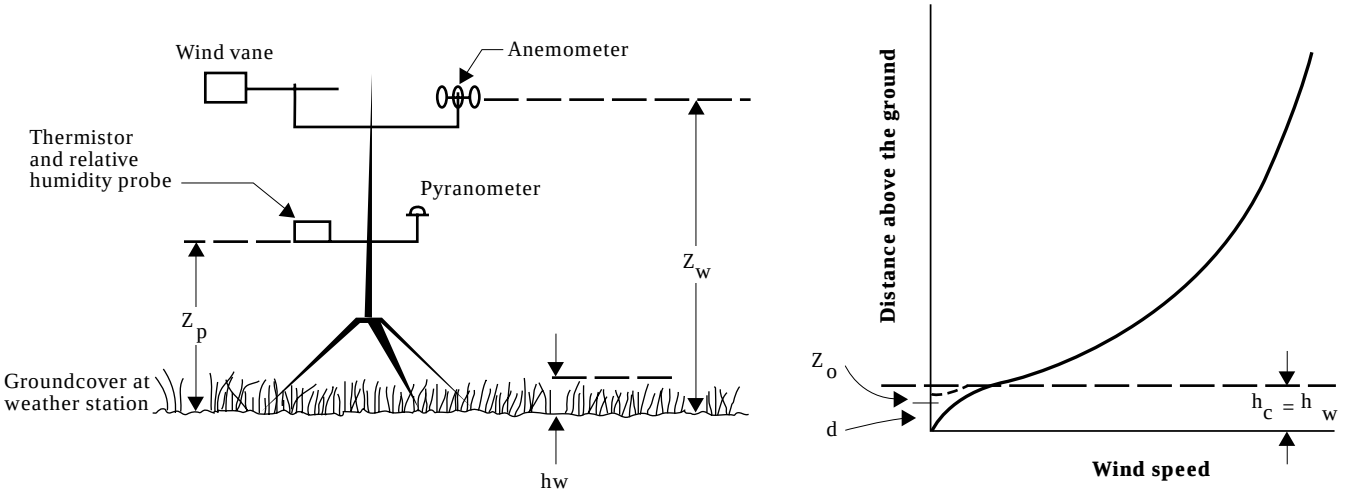


Table 2–11 Selected air properties for varying temperatures and elevations

Air temp (°F)	C_1 1/	Δ (mb/°F)	λ (lang/in)	Values of γ (mb/°F) for elevations (ft) of 0	1000	2000	3000	4000	5000	6000	7000
32	76.0	0.247	1518	0.363	0.350	0.338	0.326	0.314	0.302	0.291	0.280
34	75.7	0.265	1516	0.364	0.351	0.338	0.326	0.314	0.303	0.292	0.281
36	75.3	0.284	1514	0.364	0.351	0.339	0.326	0.314	0.303	0.292	0.281
38	74.9	0.305	1513	0.364	0.351	0.339	0.327	0.315	0.303	0.292	0.281
40	74.6	0.327	1511	0.365	0.352	0.339	0.327	0.315	0.304	0.292	0.282
42	74.2	0.350	1510	0.365	0.352	0.340	0.327	0.315	0.304	0.293	0.282
44	73.8	0.374	1508	0.366	0.353	0.340	0.328	0.316	0.304	0.293	0.282
46	73.4	0.400	1506	0.366	0.353	0.340	0.328	0.316	0.305	0.293	0.283
48	73.1	0.427	1505	0.366	0.353	0.341	0.328	0.316	0.305	0.294	0.283
50	72.7	0.456	1503	0.367	0.354	0.341	0.329	0.317	0.305	0.294	0.283
52	72.3	0.487	1502	0.367	0.354	0.341	0.329	0.317	0.306	0.294	0.283
54	72.0	0.519	1500	0.368	0.354	0.342	0.329	0.317	0.306	0.295	0.284
56	71.6	0.553	1498	0.368	0.355	0.342	0.330	0.318	0.306	0.295	0.284
58	71.2	0.590	1497	0.368	0.355	0.342	0.330	0.318	0.307	0.295	0.284
60	70.8	0.628	1495	0.369	0.356	0.343	0.330	0.318	0.307	0.296	0.285
62	70.5	0.668	1494	0.369	0.356	0.343	0.331	0.319	0.307	0.296	0.285
64	70.1	0.710	1492	0.369	0.356	0.344	0.331	0.319	0.308	0.296	0.285
66	69.7	0.755	1490	0.370	0.357	0.344	0.332	0.320	0.308	0.297	0.286
68	69.4	0.802	1489	0.370	0.357	0.344	0.332	0.320	0.308	0.297	0.286
70	69.0	0.851	1487	0.371	0.357	0.345	0.332	0.320	0.308	0.297	0.286
72	68.6	0.903	1486	0.371	0.358	0.345	0.333	0.321	0.309	0.297	0.286
74	68.2	0.958	1484	0.371	0.358	0.345	0.333	0.321	0.309	0.298	0.287
76	67.9	1.016	1483	0.372	0.359	0.346	0.333	0.321	0.309	0.298	0.287
78	67.5	1.077	1481	0.372	0.359	0.346	0.334	0.322	0.310	0.298	0.287
80	67.1	1.140	1479	0.373	0.359	0.347	0.334	0.322	0.310	0.299	0.288
82	66.7	1.207	1478	0.373	0.360	0.347	0.334	0.322	0.310	0.299	0.288
84	66.4	1.277	1476	0.373	0.360	0.347	0.335	0.323	0.311	0.299	0.288
86	66.0	1.351	1475	0.374	0.361	0.348	0.335	0.323	0.311	0.300	0.289
88	65.6	1.428	1473	0.374	0.361	0.348	0.335	0.323	0.311	0.300	0.289
90	65.3	1.509	1471	0.375	0.361	0.348	0.336	0.324	0.312	0.300	0.289
92	64.9	1.594	1470	0.375	0.362	0.349	0.336	0.324	0.312	0.301	0.290
94	64.5	1.683	1468	0.375	0.362	0.349	0.337	0.324	0.313	0.301	0.290
96	64.1	1.776	1467	0.376	0.363	0.350	0.337	0.325	0.313	0.301	0.290
98	63.8	1.874	1465	0.376	0.363	0.350	0.337	0.325	0.313	0.302	0.290
100	63.4	1.976	1463	0.377	0.363	0.350	0.338	0.325	0.314	0.302	0.291
102	63.0	2.083	1462	0.377	0.364	0.351	0.338	0.326	0.314	0.302	0.291
104	62.7	2.195	1460	0.378	0.364	0.351	0.338	0.326	0.314	0.303	0.291
106	62.3	2.312	1459	0.378	0.364	0.351	0.339	0.326	0.315	0.303	0.292
108	61.9	2.434	1457	0.378	0.365	0.352	0.339	0.327	0.315	0.303	0.292
110	61.5	2.562	1455	0.379	0.365	0.352	0.340	0.327	0.315	0.304	0.292
112	61.2	2.695	1454	0.379	0.366	0.353	0.340	0.328	0.316	0.304	0.293
114	60.8	2.834	1452	0.380	0.366	0.353	0.340	0.328	0.316	0.304	0.293
116	60.4	2.980	1451	0.380	0.366	0.353	0.341	0.328	0.316	0.305	0.293
118	60.1	3.132	1449	0.380	0.367	0.354	0.341	0.329	0.317	0.305	0.294
120	59.7	3.290	1447	0.381	0.367	0.354	0.341	0.329	0.317	0.305	0.294

1/ Note that $C_1 = 0.622\ K_1\ \lambda\rho/BP$ and has units of lang/mb/mi.

Allen (1986) showed that the roughness parameters can be predicted using the height of the reference crop (h_c):

$$Z_{om} = 0.01025\ h_c \qquad [2–42]$$

$$Z_{ov} = 0.1\ Z_{om} \qquad [2–43]$$

For a clipped grass reference crop that is 5 inches tall, the roughness parameters are:

$$Z_{om} = 0.051 \text{ feet}$$

$$Z_{ov} = 0.0051 \text{ feet}$$

The displacement height (d) is estimated using the height of the reference crop (h_c):

$$d = \left(\frac{h_c}{18}\right) \qquad [2–44]$$

Using these definitions, the aerodynamic resistance in units of days per mile is given by:

$$r_a = \frac{LN\left[\frac{97.56 Z_w}{h_c} - 5.42\right] LN\left[\frac{975.6 Z_p}{h_c} - 54.2\right]}{0.168\, U_z} \qquad [2–45]$$

where the heights Z_w and Z_p are in feet, h_c is in inches, and U_z is in miles per day. Values of the aerodynamic resistance are summarized for various configurations of weather stations and heights in table 2–12.

Jensen, et al. (1990) presented a way to estimate the canopy resistance (r_c) based upon the height and type of reference crop. The canopy resistance depends on the leaf area index of the reference crop:

$$r_c = \frac{1.863}{(0.5\ LAI)} \qquad [2–46]$$

where r_c is in units of days per mile and LAI is the leaf area index (i.e., the ratio of leaf area divided by the ground area). For a clipped grass less than 6 inches tall, Jensen, et al. (1990) recommended that:

$$LAI = 0.61\ h_c \qquad [2–47]$$

Using a constant reference crop height of 5 inches for clipped grass gives a constant canopy resistance of 1.22 days per mile.

Using these parameters, the values of γ^*, $\Delta/(\Delta + \gamma^*)$ and $\gamma/(\Delta + \gamma^*)$ can be computed. With these parameters, all terms are known for the Penman-Monteith method for a clipped grass reference crop at a height of 5 inches. The use of the Penman-Monteith method is illustrated in example 2–11.

A flow diagram was prepared for the calculations used in the Penman-Monteith method. The use of the flow diagram is illustrated in figure 2–16 for a day when the maximum and minimum temperature was 94 and 66 degrees Fahrenheit, respectively, the maximum and minimum relative humidities were 88 and 34 percent, dew point temperature was 62 degrees Fahrenheit, solar radiation was 695 langleys per day, and the wind run was 350 miles per day.

Example 2–11 assumes that wind, temperature, vapor pressure, and net radiation measurements were taken over the same type of vegetative surface as the reference crop. However, in practice, weather measurements are often taken above other surfaces. These surfaces often have vegetative heights, roughness, resistances, and corresponding temperature, vapor, and wind profiles that are different from those of the reference crop. Generally, the following procedure can be used to adjust the measured wind speed to reflect the type of conditions present at the weather station:

$$U_c = U_w \left[\frac{LN\left(97.56 \frac{Z}{h_c} - 5.42\right)}{LN\left(97.56 \frac{Z}{h_w} - 5.42\right)}\right] \qquad [2–48]$$

where:

U_c = wind speed at height Z over the reference crop (mi/d)
U_w = wind speed at height Z over the crop at the weather station (mi/d)
h_w = height of crop in the weather station (in)
h_c = height of reference crop (in)

The wind speed measured at height Z over the reference crop (U_c) can then be adjusted to the desired height using equations 2–21 and 2–22, if needed.

Table 2–12 Aerodynamic resistance (r_a in d/mi) for various wind speeds and common configurations of weather stations (based on a grass reference height of 5 inches)

Wind run	Wind speed measured at 6.6 ft			Wind speed measured at 9.8 ft		
	Height of air temperature and relative humidity sensors (ft)			Height of air temperature and relative humidity sensors (ft)		
(mi/d)	3.3	4.9	6.6	3.3	4.9	6.6
5	36.57	39.01	40.80	39.68	42.32	44.27
10	18.28	19.50	20.40	19.84	21.16	22.14
15	12.19	13.00	13.60	13.23	14.11	14.76
20	9.14	9.75	10.20	9.92	10.58	11.07
25	7.31	7.80	8.16	7.94	8.46	8.85
50	3.66	3.90	4.08	3.97	4.23	4.43
75	2.44	2.60	2.72	2.65	2.82	2.95
100	1.83	1.95	2.04	1.98	2.12	2.21
125	1.46	1.56	1.63	1.59	1.69	1.77
150	1.22	1.30	1.36	1.32	1.41	1.48
175	1.04	1.11	1.17	1.13	1.21	1.26
200	0.91	0.98	1.02	0.99	1.06	1.11
225	0.81	0.87	0.91	0.88	0.94	0.98
250	0.73	0.78	0.82	0.79	0.85	0.89
275	0.66	0.71	0.74	0.72	0.77	0.80
300	0.61	0.65	0.68	0.66	0.71	0.74
325	0.56	0.60	0.63	0.61	0.65	0.68
350	0.52	0.56	0.58	0.57	0.60	0.63
375	0.49	0.52	0.54	0.53	0.56	0.59
400	0.46	0.49	0.51	0.50	0.53	0.55
425	0.43	0.46	0.48	0.47	0.50	0.52
450	0.41	0.43	0.45	0.44	0.47	0.49
475	0.38	0.41	0.43	0.42	0.45	0.47
500	0.37	0.39	0.41	0.40	0.42	0.44
525	0.35	0.37	0.39	0.38	0.40	0.42
550	0.33	0.35	0.37	0.36	0.38	0.40
575	0.32	0.34	0.35	0.35	0.37	0.38
600	0.30	0.33	0.34	0.33	0.35	0.37
625	0.29	0.31	0.33	0.32	0.34	0.35
650	0.28	0.30	0.31	0.31	0.33	0.34
675	0.27	0.29	0.30	0.29	0.31	0.33
700	0.26	0.28	0.29	0.28	0.30	0.32
725	0.25	0.27	0.28	0.27	0.29	0.31
750	0.24	0.26	0.27	0.26	0.28	0.30

Note: Heights of 3.3, 4.9, 6.6, and 9.8 feet correspond to 1, 1.5, 2, and 3 meters.

Example 2–11 Penman-Monteith method

Required: Compute the reference crop evapotranspiration (ET_o) for a clipped grass 5 inches tall in June at the example site. Wind speed is measured at 2 m height (6.6 ft), and temperature and humidity are measured at 1.5 m (4.9 ft). Grass at the weather station is 5 inches tall.

Given:

R_n = 343 lang/d (from 623.0202(e))
G = 15 lang/d (from 623.0202(g))
$= \left(e_z^o - e_z\right) = 15.9$ mb (from 623.0202(c))

BP = 920 mb at an elevation of 2,600 ft
c_p = 0.339 lang/in/°F
r_c = 1.22 d/mi
h_c = 5 in
U_z = 260 mi/d

Solution: From equation 2–16: $\Delta = 0.051\left(\frac{164.8 + T}{157}\right)^7$

Use average daily temperature (74.5 °F), Δ = 0.97 mb/°F
λ = 1543 – 0.796 T (equation 2–19) at average temperature (T = 74.5°F)
λ = 1,484 lang/in
γ = c_p BP / 0.622 λ (equation 2–18)

$$\gamma = 0.339\,\text{lang / in / °F} \times 920\,\text{mb} \times \frac{1}{0.622} \times \frac{\text{inch}}{1{,}484\,\text{lang}} = 0.34\,\text{mb / °F}$$

From equation 2–41: $0.622K_1 \frac{\lambda\rho}{BP} = 82 - 0.186 \times T = 68.1\,\text{lang / mi / mb}$

From equation 2–45:

$$r_a = \frac{LN\left[\frac{97.56Z_w}{h_c} - 5.42\right] LN\left[\frac{975.6Z_p}{h_c} - 54.2\right]}{0.168\,U_z}$$

r_a = 0.75 d/mi

Then compute γ* from equation 2–39:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right)$$
$$= 0.34 \times \left(1 + \frac{1.22}{0.75}\right)$$
$$= 0.89\,\text{mb / °F}$$

Next, compute Δ/Δ+γ* and (γ/Δ+γ*)

$$\frac{\Delta}{(\Delta + \gamma^*)} = \frac{0.97}{(0.97 + 0.89)} = 0.52$$
$$\frac{\gamma}{(\Delta + \gamma^*)} = \frac{0.34}{(0.97 + 0.89)} = 0.18$$

Now compute ET_o (equation 2–38)

$$ET_o = \left(\frac{1}{1484}\right)\left[0.52 \times (343 - 15) + 0.18 \times 68.1 \times \frac{15.9}{0.75}\right]$$
$$ET_o = 0.29\,\text{in / day}$$

Figure 2–16 Flow diagram for computing ET_o using the Penman-Monteith method

Date 7 / 20 Day of year 201

Latitude 40 Elevation above sea level, ft 3000

Temperature and humidity relationships:

Quanity	Temp, °F	RH, %	e_z^o, mb	e_z, mb
Maximum temp	94	34	54.5	18.5
Minimum Temp	66	88	21.8	19.2
Averages	80	XXXXXX	38.2	~~XXXXX~~
Dew point temp	62	XXXXXX	e_d = 19.0	

Basic parameters

Δ for average temp $\Delta = 0.051\left(\frac{164.8+T_a}{157}\right)^7 = 0.051\left(\frac{164.8+80}{157}\right)^7$	$\Delta, mb/°F =$ 1.14
Heat of vaporization (λ) $\lambda = 1543 - 0.796\,T_a =$ 1543 - 0.796 × 80	$\lambda, lang/in =$ 1479
Barometric pressure (BP) 3000 ft $BP = 1013\left[1-\frac{E_{lev}}{145,350}\right]^{5.26}$	$BP, mb =$ 908
$\gamma = \frac{c_p\,BP}{0.622\,\lambda} = \frac{0.339 \times 908}{0.622 \times 1,479}$ c_p =0.339 langleys/inch/°F	$\gamma, mb/°F =$ 0.33

Soil heat flux

Average dailly air temperatures, °F: Today (T_a) 80 Yesterday 86 Two days ago 83 Tree days ago 77 Average temp (T_p) 82	$G = c_s\left(T_a - T_p\right) =$ 5 (80 - 82) $c_s =$ 5 langleys/°F/day	$G, lang/d =$ -10

Figure 2–16 Flow diagram for computing ET_o using the Penman-Monteith method—Continued

Radiation calculations

$a_1 = 0.26 + 0.1\ \mathrm{EXP}\left(-\left[0.0154\left(\mathrm{DOY} - 176\right)\right]^2\right) = 0.346$ 201 $\varepsilon' = a_1 - 0.044\sqrt{e_d} = 0.346 - 0.044\sqrt{19.0}$	$\varepsilon' =$ 0.154
$\sigma = 11.71 \times 10^{-8}$ 94 66 $T_s^4 = \frac{1}{2}\left[\left(\frac{5}{9}T_{max} + 255.4\right)^4 + \left(\frac{5}{9}T_{min} + 255.4\right)^4\right] = 8.11 \times 10^9$ $R_{bo} = \varepsilon'\sigma T_s^4 = 0.154 \times 11.71 \times 10^{-8} \times 8.11 \times 10^9$	$R_{bo}, lang/d =$ 146
$A = 753.6 - 6.53\ \mathrm{Lat} + 0.0057\ E_{lev} = 753.6 - 6.53 \times 40 + 0.0057 \times 3000$ $= 510$ $B = -7.1 + 6.40\ \mathrm{Lat} + 0.0030\ E_{lev} = -7.1 + 6.4 \times 40 + 0.003 \times 3000 = 258$ $R_{so} = A + B\ \mathrm{COS}\left[0.9863\left(\mathrm{DOY} - 170\right)\right] = 510 + 258\ \mathrm{COS}\left[0.9863\left(201 - 170\right)\right]$	$R_{so}, lang/d =$ 732
If R_s is measured record at right, otherwise → $R_s = \left[0.25 + 0.50\frac{n}{N}\right]R_{so}$	$R_s, lang/d =$ 695
$R_b = \left[a\left(\frac{R_s}{R_{so}}\right) + b\right]R_{bo} = \left[1.126\left(\frac{695}{732}\right) - 0.07\right]146$ If $R_s / R_{so} > 0.7$ then a = 1.126 and b = -0.07 ✓ $R_s / R_{so} \le 0.7$ then a = 1.017 and b = -0.06	$R_b, lang/d =$ 146
$\theta_d = \mathrm{SIN}^{-1}\left[0.39795\ \mathrm{COS}\left\{0.98563\left(\mathrm{DOY} - 173\right)\right\}\right] = 20.7°$ 201 $\theta_m = \mathrm{SIN}^{-1}\left[\mathrm{SIN}\left(\theta_d\right)\mathrm{SIN}\left(\mathrm{Lat}\right) + \mathrm{COS}\left(\theta_d\right)\mathrm{COS}\left(\mathrm{Lat}\right)\right] = 70.7°$ 20.7 40 $\alpha = 0.108 + 0.000939\,\theta_m + 0.257\ \mathrm{EXP}\left(\frac{-\theta_m}{57.3}\right) = 0.249$ 70.7 $R_n = \left(1 - \alpha\right)R_s - R_b = \left(1 - 0.249\right)695 - 146$	$R_n, lang/d =$ 376

Figure 2–16 Flow diagram for computing ET_o using the Penman-Monteith method—Continued

Resistance Terms (r_a and r_c):

Z_w = height of wind speed measurement = 6.6 feet

Z_p = height of air temperature measurement = 4.9 feet

U_z = wind run = 350 miles/day

r_c = 1.22 days/mile

For a 5 inch tall grass reference crop

$$r_a = \frac{LN\left(97.56\frac{Z_w}{5} - 5.42\right) LN\left(975.6\frac{Z_p}{5} - 54.2\right)}{0.168\, U_z}$$

6.6 4.9 350

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) = 0.33\left(1 + \frac{1.22}{0.56}\right)$$

$r_c, d/mi$ = 1.22

$r_a, d/mi$ = 0.56

$\gamma^* = 1.05$

Reference crop ET (ET_o)

$$\frac{0.622\, K_1 \lambda \rho}{BP} = 82 - 0.186\, T_a = 82 - 0.186 \times 80 = 67.1$$

$$ET_o = \left(\frac{1}{\lambda}\right)\left[\left(\frac{\Delta}{\Delta + \gamma^*}\right)(R_n - G) + \left(\frac{\gamma}{\Delta + \gamma^*}\right)\left(\frac{0.622\, K_1 \lambda \rho}{BP}\right)\left(\frac{e_z^o - e_z}{r_a}\right)\right]$$

$$= \left(\frac{1}{1479}\right)\left[\left(\frac{1.14}{1.14 + 1.05}\right)(376 - (-10)) + \left(\frac{0.33}{1.14 + 1.05}\right) 67.1\left(\frac{38.2 - 19}{0.56}\right)\right]$$

$$= \left(\frac{1}{1479}\right)[201 + 347]$$

ET_o = 0.37 in/d

(c) Radiation method

In some locations, climatic data required for the Penman-Monteith method are not available for the needed time period. In the evaluation by Jensen, et al. (1990), the radiation method developed by Doorenbos and Pruitt (1977) was the most accurate method that depends on solar radiation and air temperature data. This method performed very well for 9 of the 11 lysimeter sites evaluated. It was especially accurate in arid locations. However, the method greatly over estimated reference crop ET for the two lysimeter sites near the ocean in cool climates. The radiation method should not be used in such locations.

The radiation method from Doorenbos and Pruitt (1977) is given by:

$$ET_o = -0.012 + \left(\frac{\Delta}{\Delta + \gamma}\right) b_r \frac{R_s}{\lambda} \qquad [2–49]$$

where:

ET_o = evapotranspiration for clipped grass reference crop (in/d)
Δ = slope of the vapor pressure curve (mb/°F) (calculated by equation 2–16)
γ = psychrometric constant (mb/°F) (calculated by equation 2–18)
b_r = adjustment factor depending on the average relative humidity and daytime wind speed
R_s = incoming solar radiation (lang/d)
λ = heat of vaporization of water (lang/in) (equation 2–19)

The value of b_r was computed using the method recommended by Jensen, et al. (1990). It is presented in table 2–13. The average relative humidity for the adjustment factor is the average of the daily maximum and minimum relative humidities. Values for the terms in parenthesis in equation 2–49 are summarized in table 2–14. It is important to note that the values used to compute b_r are average values for the region, not daily measured values. Thus, once a value of b_r is determined for a time period at a given location, the value is constant and does not need to be computed again.

If measured solar radiation data are available, the radiation method can be easily used to reliably estimate ET_o for arid climates. When measured data are not available, estimates of solar radiation can be developed as described in 623.0202(f). Example 2–12 illustrates the use of the radiation method for June at the example site.

Example 2–12 ET_o—Radiation method

Determine: The reference crop evapotranspiration (ET_o) for June at the example site using the Radiation method.

Given: R_s = 650 lang/d
Average RH = 61%
Average wind run = 260 mi/d
λ = 1,484 lang/in (from example 2–11, Penman-Monteith method)

Solution: Assume an average day-to-night wind speed ratio of 2.
Use table 2–5 to determine mean daytime wind speed to be 14.4 mi/hr, or 346 mi/d.
Use table 2–13 to determine adjustment factor b_r:

$$b_r = 1.04$$

From example 2–11

$$\Delta = 0.97 \text{ mb} / {}^\circ\text{F}$$

$$\gamma = 0.34 \text{ mb} / {}^\circ\text{F}$$

$$\frac{\Delta}{(\Delta + \gamma)} = \frac{0.97}{(0.97 + 0.34)} = 0.74$$

$$ET_o = -0.012 + \left(0.74 \times 1.04 \times \frac{650}{1,484}\right)$$

$$ET_o = 0.33 \text{ in / d}$$

Table 2–13 Adjustment factor b_r for the radiation method [1/]

Average daytime wind speed (mi/d)	Average relative humidity (%)									
	10	20	30	40	50	60	70	80	90	100
0	1.05	1.03	1.00	0.96	0.92	0.87	0.82	0.76	0.69	0.62
20	1.07	1.04	1.01	0.98	0.94	0.89	0.83	0.77	0.70	0.63
40	1.08	1.06	1.03	0.99	0.95	0.90	0.84	0.78	0.71	0.64
60	1.10	1.07	1.04	1.00	0.96	0.91	0.85	0.79	0.72	0.65
80	1.11	1.09	1.05	1.02	0.97	0.92	0.86	0.80	0.73	0.66
100	1.13	1.10	1.07	1.03	0.98	0.93	0.87	0.81	0.74	0.66
120	1.14	1.11	1.08	1.04	1.00	0.94	0.88	0.82	0.75	0.67
140	1.15	1.13	1.09	1.05	1.01	0.95	0.89	0.83	0.76	0.68
160	1.17	1.14	1.11	1.06	1.02	0.96	0.90	0.84	0.76	0.69
180	1.18	1.15	1.12	1.08	1.03	0.97	0.91	0.85	0.77	0.69
200	1.19	1.16	1.13	1.09	1.04	0.98	0.92	0.85	0.78	0.70
220	1.21	1.18	1.14	1.10	1.05	0.99	0.93	0.86	0.79	0.70
240	1.22	1.19	1.15	1.11	1.06	1.00	0.94	0.87	0.79	0.71
260	1.23	1.20	1.16	1.12	1.07	1.01	0.95	0.88	0.80	0.72
280	1.24	1.21	1.17	1.13	1.07	1.02	0.95	0.88	0.80	0.72
300	1.26	1.22	1.18	1.14	1.08	1.02	0.96	0.89	0.81	0.73
320	1.27	1.23	1.19	1.15	1.09	1.03	0.97	0.89	0.82	0.73
340	1.28	1.24	1.20	1.15	1.10	1.04	0.97	0.90	0.82	0.74
360	1.29	1.25	1.21	1.16	1.11	1.05	0.98	0.91	0.83	0.74
380	1.30	1.26	1.22	1.17	1.11	1.05	0.98	0.91	0.83	0.74
400	1.31	1.27	1.23	1.18	1.12	1.06	0.99	0.92	0.83	0.75
420	1.32	1.28	1.24	1.19	1.13	1.07	1.00	0.92	0.84	0.75
440	1.33	1.29	1.24	1.19	1.14	1.07	1.00	0.92	0.84	0.75
460	1.34	1.30	1.25	1.20	1.14	1.08	1.01	0.93	0.84	0.75
480	1.35	1.31	1.26	1.21	1.15	1.08	1.01	0.93	0.85	0.76
500	1.35	1.31	1.27	1.21	1.15	1.09	1.01	0.94	0.85	0.76
520	1.36	1.32	1.27	1.22	1.16	1.09	1.02	0.94	0.85	0.76
540	1.37	1.33	1.28	1.22	1.16	1.10	1.02	0.94	0.85	0.76
560	1.38	1.34	1.29	1.23	1.17	1.10	1.02	0.94	0.86	0.76
580	1.39	1.34	1.29	1.23	1.17	1.10	1.03	0.95	0.86	0.76
600	1.39	1.35	1.30	1.24	1.18	1.11	1.03	0.95	0.86	0.76
620	1.40	1.35	1.30	1.24	1.18	1.11	1.03	0.95	0.86	0.76
640	1.41	1.36	1.31	1.25	1.18	1.11	1.03	0.95	0.86	0.76
660	1.41	1.37	1.31	1.25	1.19	1.11	1.04	0.95	0.86	0.76
680	1.42	1.37	1.32	1.26	1.19	1.12	1.04	0.95	0.86	0.76
700	1.42	1.38	1.32	1.26	1.19	1.12	1.04	0.95	0.86	0.76
720	1.43	1.38	1.32	1.26	1.19	1.12	1.04	0.95	0.86	0.76

1/ The equation used to compute b_r is:

$$b_r = 1.06 - 0.0013\,RH_a + 8.38\times10^{-4}\,U_d - 3.73\times10^{-6}\,RH_a\,U_d$$
$$-0.315\times10^{-4}\,RH_a^2 - 3.82\times10^{-7}\,U_d^2$$

where:

RH_a = average relative humidity (%)

U_d = average daytime wind speed (mi/d)

Table 2–14 Value of parameters used with the radiation method

Air temp (°F)	Δ (mb/°F)	λ (lang/in)	Δ/Δ+γ for elevations above sea level, ft- 0	1,000	2,000	3,000	4,000	5,000	6,000	7,000
32	0.248	1518	0.405	0.414	0.423	0.432	0.441	0.450	0.460	0.469
34	0.266	1516	0.422	0.431	0.440	0.449	0.458	0.468	0.477	0.487
36	0.286	1514	0.439	0.448	0.457	0.466	0.476	0.485	0.494	0.504
38	0.306	1513	0.456	0.465	0.474	0.483	0.493	0.502	0.511	0.521
40	0.328	1511	0.473	0.482	0.491	0.500	0.510	0.519	0.528	0.538
42	0.351	1510	0.490	0.499	0.508	0.517	0.526	0.536	0.545	0.554
44	0.375	1508	0.506	0.515	0.524	0.534	0.543	0.552	0.561	0.571
46	0.401	1506	0.523	0.532	0.541	0.550	0.559	0.568	0.577	0.587
48	0.429	1505	0.539	0.548	0.557	0.566	0.575	0.584	0.593	0.602
50	0.458	1503	0.555	0.564	0.573	0.582	0.591	0.600	0.609	0.618
52	0.488	1502	0.570	0.579	0.588	0.597	0.606	0.615	0.624	0.633
54	0.521	1500	0.586	0.595	0.603	0.612	0.621	0.630	0.638	0.647
56	0.555	1498	0.601	0.610	0.618	0.627	0.636	0.644	0.653	0.661
58	0.591	1497	0.616	0.624	0.633	0.641	0.650	0.658	0.667	0.675
60	0.629	1495	0.630	0.639	0.647	0.655	0.664	0.672	0.680	0.688
62	0.670	1494	0.644	0.653	0.661	0.669	0.677	0.685	0.693	0.701
64	0.712	1492	0.658	0.666	0.674	0.682	0.690	0.698	0.706	0.714
66	0.757	1490	0.671	0.679	0.687	0.695	0.703	0.711	0.718	0.726
68	0.804	1489	0.684	0.692	0.700	0.708	0.715	0.723	0.730	0.738
70	0.853	1487	0.697	0.704	0.712	0.720	0.727	0.734	0.742	0.749
72	0.906	1486	0.709	0.716	0.724	0.731	0.738	0.746	0.753	0.760
74	0.961	1484	0.721	0.728	0.735	0.742	0.749	0.756	0.763	0.770
76	1.018	1483	0.732	0.739	0.746	0.753	0.760	0.767	0.773	0.780
78	1.079	1481	0.743	0.750	0.757	0.764	0.770	0.777	0.783	0.790
80	1.143	1479	0.754	0.760	0.767	0.774	0.780	0.786	0.793	0.799
82	1.210	1478	0.764	0.771	0.777	0.783	0.789	0.796	0.802	0.808
84	1.280	1476	0.774	0.780	0.786	0.792	0.799	0.804	0.810	0.816
86	1.354	1475	0.783	0.789	0.795	0.801	0.807	0.813	0.819	0.824
88	1.431	1473	0.792	0.798	0.804	0.810	0.816	0.821	0.827	0.832
90	1.512	1471	0.801	0.807	0.813	0.818	0.824	0.829	0.834	0.839
92	1.597	1470	0.810	0.815	0.821	0.826	0.831	0.836	0.841	0.846
94	1.687	1468	0.818	0.823	0.828	0.833	0.839	0.844	0.848	0.853
96	1.780	1467	0.825	0.831	0.836	0.841	0.846	0.850	0.855	0.860
98	1.878	1465	0.833	0.838	0.843	0.848	0.852	0.857	0.861	0.866
100	1.980	1463	0.840	0.845	0.850	0.854	0.859	0.863	0.868	0.872
102	2.087	1462	0.847	0.851	0.856	0.860	0.865	0.869	0.873	0.878
104	2.199	1460	0.853	0.858	0.862	0.867	0.871	0.875	0.879	0.883
106	2.316	1459	0.860	0.864	0.868	0.872	0.876	0.880	0.884	0.888
108	2.439	1457	0.866	0.870	0.874	0.878	0.882	0.886	0.889	0.893
110	2.567	1455	0.871	0.875	0.879	0.883	0.887	0.891	0.894	0.898
112	2.700	1454	0.877	0.881	0.884	0.888	0.892	0.895	0.899	0.902
114	2.840	1452	0.882	0.886	0.889	0.893	0.896	0.900	0.903	0.906
116	2.986	1451	0.887	0.891	0.894	0.897	0.901	0.904	0.907	0.910
118	3.138	1449	0.892	0.895	0.899	0.902	0.905	0.908	0.911	0.914
120	3.296	1447	0.896	0.900	0.903	0.906	0.909	0.912	0.915	0.918

(d) Temperature method

Estimates of crop water use based solely on air temperature have been widely used in several places of the United States and internationally. Jensen, et al. (1990) found that the version of the Blaney-Criddle method developed by Doorenbos and Pruitt (1977) was the most accurate temperature-based method evaluated for estimating crop ET_o. This technique, commonly referred to as the FAO-Blaney-Criddle method, is described by:

$$ET_o = c_e\left(a_t + b_t pT\right) \qquad [2–50]$$

where:

ET_o = evapotranspiration for clipped grass reference crop (in/d)
p = mean daily percent of annual daytime hours
T = mean air temperature for the period (°F)
a_t and b_t = adjustment factors based on the climate of the region
c_e = adjustment factor based on elevation above sea level

Values of a_t are presented in table 2–15 as a function of the mean minimum relative humidity in percent (RH_{min}) and the mean ratio of actual to possible sunshine hours (n/N).

The value of b_t depends on the minimum relative humidity, sunshine ratio, and the mean day time wind speed. Adjustment factor b_t can be computed as:

$$b_t = b_n + b_u \qquad [2–51]$$

Values of b_n and b_u are summarized in tables 2–16 and 2–17, respectively, along with the equations to use in calculating these factors.

The climatic parameters used to compute a_t and b_t are regional average values, not daily measured values. Thus, once values of a_t and b_t are determined for a time of year and a location, they can be used for different days in the period and for all years analyzed.

The elevation correction factor c_e is given as:

$$c_e = 0.01 + 3.049 \times 10^{-7}\ E_{lev} \qquad [2–52]$$

where:

E_{lev} = elevation above sea level, ft.

The mean daily percent of annual daytime hours (p) is the ratio of the hours of daylight for a day in the middle of the respective month, relative to the hours of daylight for the year. Values of p are listed in table 2–18 as a function of latitude. The mean daily percent of annual daytime hours (p) can be computed from:

$$p = 0.00304\ COS^{-1}\left[\frac{-SIN\left(\theta_d\right)SIN\left(Lat\right)}{COS\left(\theta_d\right)COS\left(Lat\right)}\right]$$

with: [2–53]

$$\theta_d = SIN^{-1}\left\{0.39795\ COS\left[0.98563\left(DOY - 173\right)\right]\right\}$$

where:

θ_d = solar declination angle (degrees)
DOY = day of year (see Appendix B, Day of Year Calendar)
Lat = latitude (°N)

Calculations for the southern latitudes require a shift in time of 6 months as shown in table 2–18. For the southern hemisphere, the constant –173 in equation 2–53 should be replaced with +9.5 to compute p.

Example 2–13 illustrates computation of average ET_o for June at the example site using the FAO Blaney-Criddle method.

Example 2–13 FAO Blaney-Criddle

Compute: ET_o for June at the example site.

Given: Average daily temperature = 74.5 °F
n/N = 0.74
Elevation = 2,600 feet
Latitude = 38° N

Using data as in example 2–2, vapor pressure deficit:

$$e_d = 15.9 \text{ mb and } e^o_{T_{max}} = 45.2 \text{ mb}$$

From example 2–12, ET_o—Radiation method:
Mean daytime wind speed = 346 mi/d

Solution: Mean minimum relative humidity $\left(RH_{min}\right) = \left(\frac{e_d}{e^o_{T_{max}}}\right)100$

$$RH_{min} = \left(\frac{15.9 \text{ mb}}{45.2 \text{ mb}}\right) \times 100 = 35\%$$

$$c_e = 0.01 + 3.049 \times 10^{-7} \times 2,600 = 0.0108$$

Using table 2–15 $a_t = -7.9$
Using table 2–16 $b_n = 1.31$
Using table 2–17 $b_u = 0.29$
Using table 2–18 $p = 0.33$

$$b_t = 1.31 + 0.29 = 1.60$$

From equation 2–50:

$$ET_o = c_e\left(a_t + b_t pT\right)$$

$$ET_o = 0.0108 \times \left[-7.9 + \left(1.60 \times 0.33 \times 74.5\right)\right]$$

$$ET_o = 0.34 \text{ in / day}$$

Table 2–15 Values of adjustment factor a_t for use in equation 2–50 [1/]

Mean minimum relative humidity (%)	Ratio of actual to possible sunshine (n/N)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
10	-5.78	-6.17	-6.56	-6.96	-7.35	-7.74	-8.14	-8.53	-8.93	-9.32
12	-5.74	-6.14	-6.53	-6.92	-7.32	-7.71	-8.10	-8.50	-8.89	-9.29
14	-5.71	-6.10	-6.50	-6.89	-7.28	-7.68	-8.07	-8.46	-8.86	-9.25
16	-5.67	-6.07	-6.46	-6.86	-7.25	-7.64	-8.04	-8.43	-8.82	-9.22
18	-5.64	-6.03	-6.43	-6.82	-7.21	-7.61	-8.00	-8.40	-8.79	-9.18
20	-5.61	-6.00	-6.39	-6.79	-7.18	-7.57	-7.97	-8.36	-8.76	-9.15
22	-5.57	-5.97	-6.36	-6.75	-7.15	-7.54	-7.93	-8.33	-8.72	-9.12
24	-5.54	-5.93	-6.33	-6.72	-7.11	-7.51	-7.90	-8.29	-8.69	-9.08
26	-5.50	-5.90	-6.29	-6.69	-7.08	-7.47	-7.87	-8.26	-8.65	-9.05
28	-5.47	-5.86	-6.26	-6.65	-7.05	-7.44	-7.83	-8.23	-8.62	-9.01
30	-5.44	-5.83	-6.22	-6.62	-7.01	-7.41	-7.80	-8.19	-8.59	-8.98
32	-5.40	-5.80	-6.19	-6.58	-6.98	-7.37	-7.77	-8.16	-8.55	-8.95
34	-5.37	-5.76	-6.16	-6.55	-6.94	-7.34	-7.73	-8.13	-8.52	-8.91
36	-5.34	-5.73	-6.12	-6.52	-6.91	-7.30	-7.70	-8.09	-8.49	-8.88
38	-5.30	-5.70	-6.09	-6.48	-6.88	-7.27	-7.66	-8.06	-8.45	-8.84
40	-5.27	-5.66	-6.06	-6.45	-6.84	-7.24	-7.63	-8.02	-8.42	-8.81
42	-5.23	-5.63	-6.02	-6.41	-6.81	-7.20	-7.60	-7.99	-8.38	-8.78
44	-5.20	-5.59	-5.99	-6.38	-6.77	-7.17	-7.56	-7.96	-8.35	-8.74
46	-5.17	-5.56	-5.95	-6.35	-6.74	-7.13	-7.53	-7.92	-8.32	-8.71
48	-5.13	-5.53	-5.92	-6.31	-6.71	-7.10	-7.49	-7.89	-8.28	-8.68
50	-5.10	-5.49	-5.89	-6.28	-6.67	-7.07	-7.46	-7.85	-8.25	-8.64
52	-5.06	-5.46	-5.85	-6.25	-6.64	-7.03	-7.43	-7.82	-8.21	-8.61
54	-5.03	-5.42	-5.82	-6.21	-6.61	-7.00	-7.39	-7.79	-8.18	-8.57
56	-5.00	-5.39	-5.78	-6.18	-6.57	-6.97	-7.36	-7.75	-8.15	-8.54
58	-4.96	-5.36	-5.75	-6.14	-6.54	-6.93	-7.33	-7.72	-8.11	-8.51
60	-4.93	-5.32	-5.72	-6.11	-6.50	-6.90	-7.29	-7.69	-8.08	-8.47
62	-4.90	-5.29	-5.68	-6.08	-6.47	-6.86	-7.26	-7.65	-8.04	-8.44
64	-4.86	-5.26	-5.65	-6.04	-6.44	-6.83	-7.22	-7.62	-8.01	-8.40
66	-4.83	-5.22	-5.61	-6.01	-6.40	-6.80	-7.19	-7.58	-7.98	-8.37
68	-4.79	-5.19	-5.58	-5.97	-6.37	-6.76	-7.16	-7.55	-7.94	-8.34
70	-4.76	-5.15	-5.55	-5.94	-6.33	-6.73	-7.12	-7.52	-7.91	-8.30
72	-4.73	-5.12	-5.51	-5.91	-6.30	-6.69	-7.09	-7.48	-7.88	-8.27
74	-4.69	-5.09	-5.48	-5.87	-6.27	-6.66	-7.05	-7.45	-7.84	-8.24
76	-4.66	-5.05	-5.45	-5.84	-6.23	-6.63	-7.02	-7.41	-7.81	-8.20
78	-4.62	-5.02	-5.41	-5.81	-6.20	-6.59	-6.99	-7.38	-7.77	-8.17
80	-4.59	-4.98	-5.38	-5.77	-6.17	-6.56	-6.95	-7.35	-7.74	-8.13
82	-4.56	-4.95	-5.34	-5.74	-6.13	-6.53	-6.92	-7.31	-7.71	-8.10
84	-4.52	-4.92	-5.31	-5.70	-6.10	-6.49	-6.89	-7.28	-7.67	-8.07
86	-4.49	-4.88	-5.28	-5.67	-6.06	-6.46	-6.85	-7.24	-7.64	-8.03
88	-4.46	-4.85	-5.24	-5.64	-6.03	-6.42	-6.82	-7.21	-7.60	-8.00
90	-4.42	-4.81	-5.21	-5.60	-6.00	-6.39	-6.78	-7.18	-7.57	-7.96

1/ $a_t = 3.937\left(0.0043\ RH_{min} - \frac{n}{N} - 1.41\right)$

Table 2–16 Values of adjustment factor b_n for use in equation 2–51 1/

Mean minimum relative humidity (%)	Ratio of actual to possible sunshine (n/N)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
10	0.88	0.98	1.08	1.18	1.28	1.39	1.49	1.59	1.69	1.79
12	0.87	0.97	1.07	1.17	1.27	1.37	1.47	1.57	1.67	1.77
14	0.86	0.96	1.06	1.16	1.26	1.35	1.45	1.55	1.65	1.75
16	0.85	0.95	1.05	1.14	1.24	1.34	1.44	1.53	1.63	1.73
18	0.84	0.94	1.03	1.13	1.23	1.32	1.42	1.52	1.61	1.71
20	0.83	0.93	1.02	1.12	1.21	1.31	1.40	1.50	1.59	1.69
22	0.82	0.92	1.01	1.11	1.20	1.29	1.39	1.48	1.57	1.67
24	0.81	0.91	1.00	1.09	1.18	1.28	1.37	1.46	1.56	1.65
26	0.80	0.90	0.99	1.08	1.17	1.26	1.35	1.44	1.54	1.63
28	0.80	0.89	0.98	1.07	1.16	1.25	1.34	1.43	1.52	1.61
30	0.79	0.88	0.96	1.05	1.14	1.23	1.32	1.41	1.50	1.59
32	0.78	0.86	0.95	1.04	1.13	1.22	1.30	1.39	1.48	1.57
34	0.77	0.85	0.94	1.03	1.11	1.20	1.29	1.37	1.46	1.55
36	0.76	0.84	0.93	1.01	1.10	1.18	1.27	1.36	1.44	1.53
38	0.75	0.83	0.92	1.00	1.09	1.17	1.25	1.34	1.42	1.51
40	0.74	0.82	0.91	0.99	1.07	1.15	1.24	1.32	1.40	1.49
42	0.73	0.81	0.89	0.98	1.06	1.14	1.22	1.30	1.38	1.47
44	0.72	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.37	1.45
46	0.71	0.79	0.87	0.95	1.03	1.11	1.19	1.27	1.35	1.43
48	0.70	0.78	0.86	0.94	1.01	1.09	1.17	1.25	1.33	1.41
50	0.69	0.77	0.85	0.92	1.00	1.08	1.15	1.23	1.31	1.39
52	0.68	0.76	0.83	0.91	0.99	1.06	1.14	1.21	1.29	1.36
54	0.67	0.75	0.82	0.90	0.97	1.05	1.12	1.20	1.27	1.34
56	0.66	0.74	0.81	0.88	0.96	1.03	1.10	1.18	1.25	1.32
58	0.65	0.73	0.80	0.87	0.94	1.02	1.09	1.16	1.23	1.30
60	0.65	0.72	0.79	0.86	0.93	1.00	1.07	1.14	1.21	1.28
62	0.64	0.71	0.78	0.85	0.91	0.98	1.05	1.12	1.19	1.26
64	0.63	0.69	0.76	0.83	0.90	0.97	1.04	1.11	1.18	1.24
66	0.62	0.68	0.75	0.82	0.89	0.95	1.02	1.09	1.16	1.22
68	0.61	0.67	0.74	0.81	0.87	0.94	1.00	1.07	1.14	1.20
70	0.60	0.66	0.73	0.79	0.86	0.92	0.99	1.05	1.12	1.18
72	0.59	0.65	0.72	0.78	0.84	0.91	0.97	1.04	1.10	1.16
74	0.58	0.64	0.70	0.77	0.83	0.89	0.95	1.02	1.08	1.14
76	0.57	0.63	0.69	0.75	0.82	0.88	0.94	1.00	1.06	1.12
78	0.56	0.62	0.68	0.74	0.80	0.86	0.92	0.98	1.04	1.10
80	0.55	0.61	0.67	0.73	0.79	0.85	0.91	0.96	1.02	1.08
82	0.54	0.60	0.66	0.72	0.77	0.83	0.89	0.95	1.00	1.06
84	0.53	0.59	0.65	0.70	0.76	0.82	0.87	0.93	0.99	1.04
86	0.52	0.58	0.63	0.69	0.74	0.80	0.86	0.91	0.97	1.02
88	0.51	0.57	0.62	0.68	0.73	0.78	0.84	0.89	0.95	1.00
90	0.50	0.56	0.61	0.66	0.72	0.77	0.82	0.88	0.93	0.98

1/ $b_n = 0.82 - 0.0041\,RH_{min} + 1.07\,\frac{n}{N} - 0.006\,RH_{min}\,\frac{n}{N}$

Table 2–17 Values of adjustment factor b_u for use in equation 2–51 [1/]

Mean minimum relative humidity (%)	Mean daytime wind speed at 2 meters above the ground, mi/d												
	50	100	150	200	250	300	350	400	450	500	600	700	800
10	0.06	0.11	0.17	0.22	0.28	0.34	0.39	0.45	0.50	0.56	0.67	0.78	0.90
12	0.05	0.11	0.16	0.22	0.27	0.33	0.38	0.44	0.49	0.55	0.66	0.77	0.88
14	0.05	0.11	0.16	0.21	0.27	0.32	0.38	0.43	0.48	0.54	0.64	0.75	0.86
16	0.05	0.11	0.16	0.21	0.26	0.32	0.37	0.42	0.47	0.53	0.63	0.74	0.84
18	0.05	0.10	0.15	0.21	0.26	0.31	0.36	0.41	0.46	0.52	0.62	0.72	0.82
20	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.71	0.81
22	0.05	0.10	0.15	0.20	0.25	0.30	0.34	0.39	0.44	0.49	0.59	0.69	0.79
24	0.05	0.10	0.14	0.19	0.24	0.29	0.34	0.39	0.43	0.48	0.58	0.67	0.77
26	0.05	0.09	0.14	0.19	0.24	0.28	0.33	0.38	0.42	0.47	0.56	0.66	0.75
28	0.05	0.09	0.14	0.18	0.23	0.28	0.32	0.37	0.41	0.46	0.55	0.64	0.73
30	0.04	0.09	0.13	0.18	0.22	0.27	0.31	0.36	0.40	0.45	0.54	0.63	0.72
32	0.04	0.09	0.13	0.17	0.22	0.26	0.31	0.35	0.39	0.44	0.52	0.61	0.70
34	0.04	0.09	0.13	0.17	0.21	0.26	0.30	0.34	0.38	0.43	0.51	0.60	0.68
36	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.41	0.50	0.58	0.66
38	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40	0.48	0.56	0.65
40	0.04	0.08	0.12	0.16	0.20	0.24	0.27	0.31	0.35	0.39	0.47	0.55	0.63
42	0.04	0.08	0.11	0.15	0.19	0.23	0.27	0.30	0.34	0.38	0.46	0.53	0.61
44	0.04	0.07	0.11	0.15	0.18	0.22	0.26	0.30	0.33	0.37	0.44	0.52	0.59
46	0.04	0.07	0.11	0.14	0.18	0.22	0.25	0.29	0.32	0.36	0.43	0.50	0.57
48	0.03	0.07	0.10	0.14	0.17	0.21	0.24	0.28	0.31	0.35	0.42	0.49	0.56
50	0.03	0.07	0.10	0.13	0.17	0.20	0.24	0.27	0.30	0.34	0.40	0.47	0.54
52	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.39	0.46	0.52
54	0.03	0.06	0.09	0.13	0.16	0.19	0.22	0.25	0.28	0.31	0.38	0.44	0.50
56	0.03	0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.30	0.36	0.42	0.48
58	0.03	0.06	0.09	0.12	0.15	0.17	0.20	0.23	0.26	0.29	0.35	0.41	0.47
60	0.03	0.06	0.08	0.11	0.14	0.17	0.20	0.22	0.25	0.28	0.34	0.39	0.45
62	0.03	0.05	0.08	0.11	0.13	0.16	0.19	0.22	0.24	0.27	0.32	0.38	0.43
64	0.03	0.05	0.08	0.10	0.13	0.15	0.18	0.21	0.23	0.26	0.31	0.36	0.41
66	0.02	0.05	0.07	0.10	0.12	0.15	0.17	0.20	0.22	0.25	0.30	0.35	0.39
68	0.02	0.05	0.07	0.09	0.12	0.14	0.16	0.19	0.21	0.24	0.28	0.33	0.38
70	0.02	0.04	0.07	0.09	0.11	0.13	0.16	0.18	0.20	0.22	0.27	0.31	0.36
72	0.02	0.04	0.06	0.09	0.11	0.13	0.15	0.17	0.19	0.21	0.26	0.30	0.34
74	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.24	0.28	0.32
76	0.02	0.04	0.06	0.08	0.10	0.11	0.13	0.15	0.17	0.19	0.23	0.27	0.31
78	0.02	0.04	0.05	0.07	0.09	0.11	0.13	0.14	0.16	0.18	0.22	0.25	0.29
80	0.02	0.03	0.05	0.07	0.08	0.10	0.12	0.13	0.15	0.17	0.20	0.24	0.27
82	0.02	0.03	0.05	0.06	0.08	0.09	0.11	0.13	0.14	0.16	0.19	0.22	0.25
84	0.01	0.03	0.04	0.06	0.07	0.09	0.10	0.12	0.13	0.15	0.18	0.20	0.23
86	0.01	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.13	0.16	0.19	0.22
88	0.01	0.02	0.04	0.05	0.06	0.07	0.09	0.10	0.11	0.12	0.15	0.17	0.20
90	0.01	0.02	0.03	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.14	0.16	0.18

1/ $$b_u = \frac{\left(1.23\ U_d - 0.0112\ RH_{min} U_d\right)}{1{,}000}$$

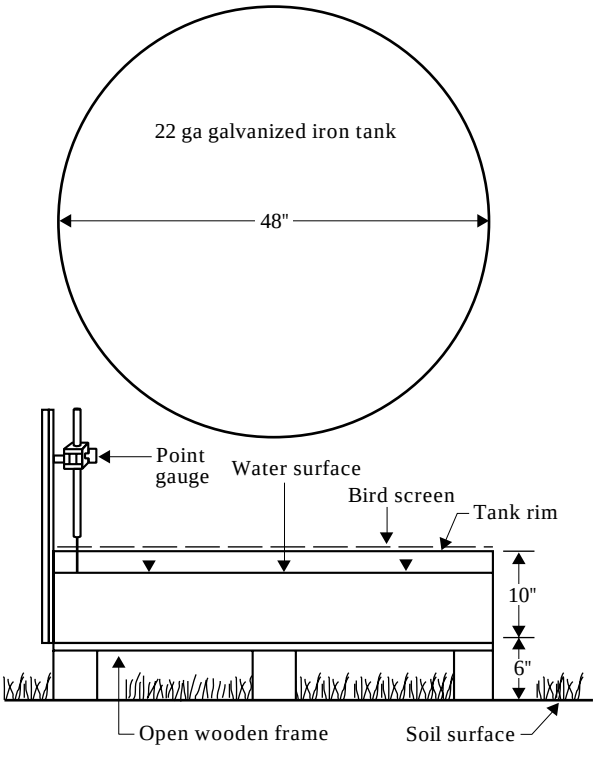
Table 2–18 Daily percent of annual daytime hours (p)

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
64	0.11	0.18	0.26	0.33	0.41	0.46	0.44	0.36	0.29	0.21	0.14	0.09
62	0.13	0.19	0.26	0.33	0.39	0.44	0.42	0.36	0.29	0.22	0.15	0.11
60	0.15	0.20	0.26	0.32	0.38	0.42	0.40	0.35	0.29	0.22	0.16	0.13
58	0.16	0.20	0.26	0.32	0.37	0.41	0.39	0.34	0.29	0.23	0.17	0.14
56	0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.34	0.29	0.23	0.18	0.15
54	0.18	0.21	0.26	0.31	0.36	0.38	0.37	0.33	0.28	0.23	0.19	0.16
52	0.18	0.22	0.26	0.31	0.35	0.38	0.37	0.33	0.28	0.24	0.20	0.17
50	0.19	0.22	0.26	0.31	0.35	0.37	0.36	0.33	0.28	0.24	0.20	0.18
48	0.20	0.23	0.26	0.30	0.34	0.36	0.35	0.32	0.28	0.24	0.21	0.19
46	0.20	0.23	0.27	0.30	0.34	0.35	0.35	0.32	0.28	0.24	0.21	0.19
44	0.21	0.23	0.27	0.30	0.33	0.35	0.34	0.32	0.28	0.25	0.22	0.20
42	0.21	0.24	0.27	0.30	0.33	0.34	0.34	0.31	0.28	0.25	0.22	0.20
40	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
38	0.22	0.24	0.27	0.30	0.32	0.33	0.33	0.31	0.28	0.25	0.23	0.21
36	0.22	0.24	0.27	0.29	0.32	0.33	0.32	0.30	0.28	0.25	0.23	0.22
34	0.23	0.25	0.27	0.29	0.31	0.33	0.32	0.30	0.28	0.25	0.23	0.22
32	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.26	0.24	0.23
30	0.23	0.25	0.27	0.29	0.31	0.32	0.31	0.30	0.28	0.26	0.24	0.23
28	0.24	0.25	0.27	0.29	0.31	0.31	0.31	0.30	0.28	0.26	0.24	0.23
26	0.24	0.25	0.27	0.29	0.30	0.31	0.31	0.29	0.28	0.26	0.24	0.24
24	0.24	0.26	0.27	0.29	0.30	0.31	0.30	0.29	0.28	0.26	0.25	0.24
22	0.25	0.26	0.27	0.29	0.30	0.30	0.30	0.29	0.28	0.26	0.25	0.24
20	0.25	0.26	0.27	0.28	0.30	0.30	0.30	0.29	0.28	0.26	0.25	0.25
18	0.25	0.26	0.27	0.28	0.29	0.30	0.30	0.29	0.28	0.26	0.25	0.25
16	0.25	0.26	0.27	0.28	0.29	0.30	0.29	0.29	0.28	0.27	0.26	0.25
14	0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.26
12	0.26	0.27	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.26
10	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
8	0.26	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.26
6	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
4	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
2	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
0	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Latitude South	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**

(e) Evaporation pan method

Reference crop water evapotranspiration can be estimated by measuring the rate of evaporation from a shallow, open-faced pan. When the pan is installed to specific recommendations, it is referred to as a Class A standard pan. Class A evaporation pans are mounted on an open wooden frame with the bottom of the pan 6 inches above the ground (fig. 2–17). The water level in the pan should be maintained 2 to 3 inches below the rim of the pan. The pan should be painted with aluminum paint annually, and water should be replaced as needed to prevent turbidity. The water added to the pan should be at the same temperature as the water in the pan.

Figure 2–17 Schematic diagram of a Class A evaporation pan



The reference crop ET can be approximated by multiplying the pan evaporation times a parameter called the pan coefficient:

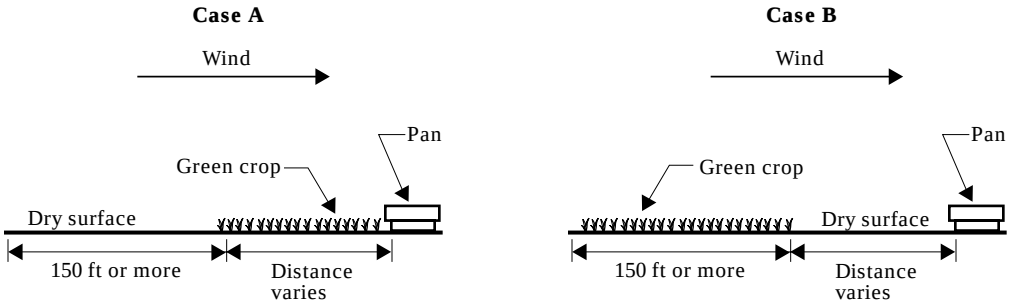
$$ET_o = k_p E_{pan} \qquad [2–54]$$

where:

ET_o = the evapotranspiration for a clipped grass reference crop (in/d)
k_p = pan coefficient
E_{pan} = evaporation from the pan (in/d)

Doorenbos and Pruitt (1977) developed a procedure to predict k_p for Class A evaporation pans. The pan coefficient for Class A pans varies depending on the climate and the type of soil cover surrounding the pan. Doorenbos and Pruitt defined two general cases that represent conditions surrounding most pans (table 2–19). Based on the type of installation, an approximate pan coefficient can be determined using the average daily wind speed and the mean relative humidity. For the example site, the mean relative humidity in June is about 61 percent. Also, the mean wind speed in June is 260 miles per day. Therefore, if the pan is surrounded by a green crop for a distance of 30 feet, the pan coefficient is about 0.6. Like the temperature and radiation methods, the climatic parameters used to determine k_p are average values for a region and time, not daily values each year.

Table 2–19 Pan coefficients for Class A evaporation pans for different ground cover and levels of mean relative humidity and 24-hour wind run



Class A pan		Case A - - pan surrounded by short green crop - -				Case B 1/ - - - pan surrounded by dry-fallow land - - -		
Mean relative humidity (%)		Low <40	Medium 40-70	High >70		Low <40	Medium 40-70	High >70
Average daily wind run (mi/d)	Upwind distance of green crop (ft)				Upwind distance of dry fallow (ft)			
Light 120	0	0.55	0.65	0.75	0	0.7	0.8	0.85
	30	0.65	0.75	0.85	30	0.6	0.7	0.8
	300	0.7	0.8	0.85	300	0.55	0.65	0.75
	3,000	0.75	0.85	0.85	3,000	0.5	0.6	0.7
Moderate 120–240	0	0.5	0.6	0.65	0	0.65	0.75	0.8
	30	0.6	0.7	0.75	30	0.55	0.65	0.7
	300	0.65	0.75	0.8	300	0.5	0.6	0.65
	3,000	0.7	0.8	0.8	3,000	0.45	0.55	0.6
Strong 240-480	0	0.45	0.5	0.60	0	0.6	0.65	0.7
	30	0.55	0.6	0.65	30	0.5	0.55	0.65
	300	0.6	0.65	0.7	00	0.45	0.50	0.6
	3,000	0.65	0.7	0.75	3,000	0.4	0.45	0.55
Very strong >480	0	0.4	0.45	0.5	0	0.5	0.6	0.65
	30	0.45	0.55	0.6	30	0.45	0.5	0.55
	300	0.5	0.6	0.65	300	0.4	0.45	0.5
	3000	0.55	0.6	0.65	3000	0.35	0.4	0.45

Adapted from J. Doorenbos and W.O. Pruitt (1977).

1/ For extensive areas of bare-fallow soils and areas without agricultural development, reduce k_p values by 20 percent under hot, windy conditions; by 5 to 10 percent for moderate wind, temperature, and humidity conditions.

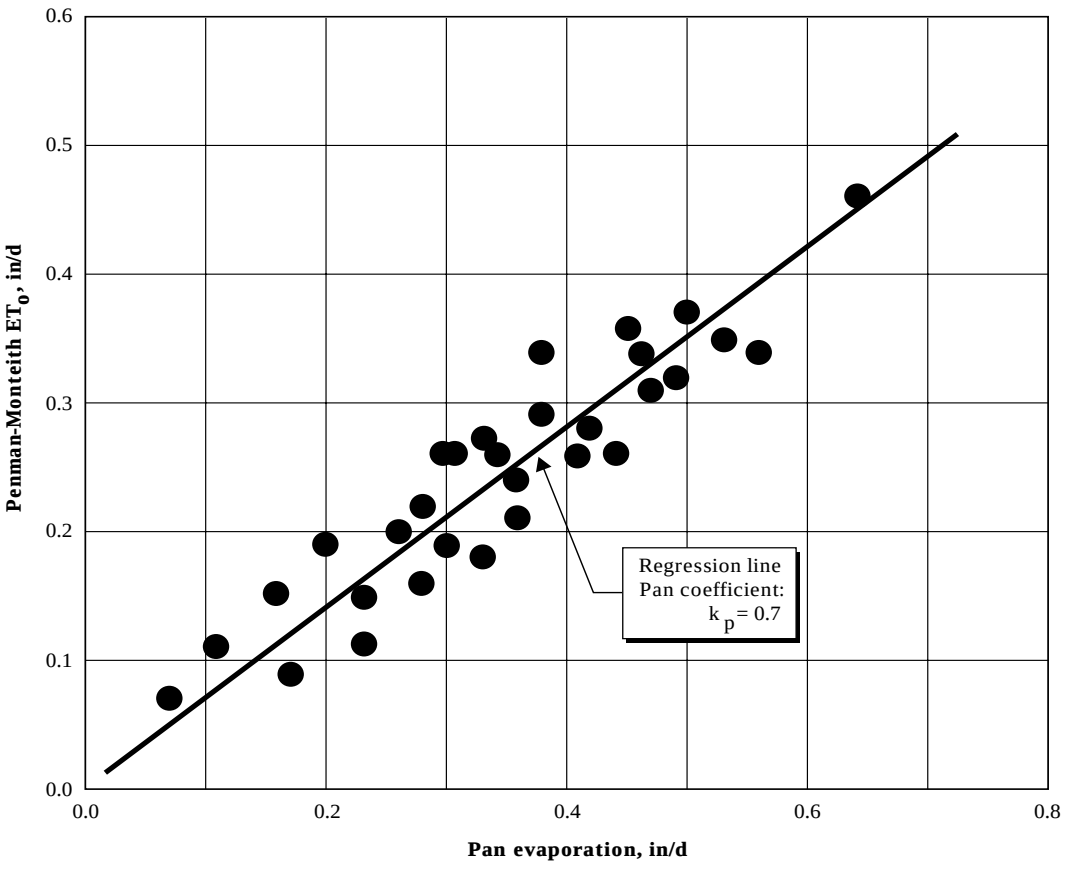
Note: These coefficients are used to estimate the evapotranspiration for a clipped grass reference crop. Crop coefficients as discussed in 623.0204 are required to predict actual crop evapotranspiration rates.

Locally calibrated pan coefficients can also be determined by correlating pan evaporation to ET_o predicted from other methods. This process is often required for long-term studies where adequate climatic data as required for the Penman-Monteith method are available for only a part of the duration of the study. If evaporation pan data are available for the duration of the study, then the climatic data can be used with the Penman-Monteith method to predict ET_o values. Then the predicted ET_o values can be used to compute a pan coefficient for the specific pan. Sometimes this procedure is used to compute monthly pan coefficients. Example 2–14 illustrates the calibration procedure.

Evaporation pans have been used extensively to predict ET_o and for irrigation management. They are simple to install and use. However, the pans require careful maintenance. The conditions surrounding the pan must be carefully managed to prevent drift in the pan coefficient.

One disadvantage of the evaporation pan is that the water in the pan stores and releases energy differently than crop surfaces. When the air temperature changes, it takes longer for the water to change temperature. Therefore, the energy that would normally be used for ET_o is used to heat water. Conversely, as air cools, there is a lag in the time required to cool the water. The result of this energy storage is that the evaporation rate from the pan generally has a narrower range of daily rates of crop water use. Over long periods, the daily rate of energy storage is small compared to the energy used during the period to evaporate water. Thus, evaporation pans are usually accurate for periods longer than 10 days. If daily rates or short period estimates are needed, the evaporation pan is not recommended.

Figure 2–18 Plot of pan evaporation against Penman-Monteith ET_o to determine a pan coefficient



(f) Summary

Several factors affect the selection of the proper ET_o method for a specific application. Personal judgment is required for each application. If results of an application carry high risks preliminary investigation comparing alternative methods may be warranted. The four methods in this section present alternatives that will satisfy most applications.

Example 2–14 Local calibration of a pan coefficient

Required: Determine a locally calibrated pan coefficient for the Penman-Monteith ET_o and evaporation pan data given below.

Given: The following daily values have been obtained for July at a site.

Day of month	Penman-Monteith ET_o values (in/d)	Pan evaporation (in/d)	Day of month	Penman-Monteith ET_o values (in/d)	Pan evaporation (in/d)
1	0.26	0.30	16	0.46	0.64
2	0.31	0.47	17	0.34	0.56
3	0.37	0.50	18	0.35	0.53
4	0.29	0.38	19	0.18	0.33
5	0.20	0.26	20	0.15	0.16
6	0.19	0.20	21	0.11	0.11
7	0.19	0.30	22	0.22	0.28
8	0.15	0.23	23	0.26	0.31
9	0.09	0.17	24	0.26	0.41
10	0.21	0.36	25	0.28	0.42
11	0.26	0.44	26	0.32	0.49
12	0.34	0.46	27	0.36	0.45
13	0.27	0.33	28	0.34	0.38
14	0.16	0.28	29	0.26	0.34
15	0.11	0.23	30	0.24	0.36
			31	0.07	0.07

Solution: Plot the evaporation pan data on the abscissa and the Penman-Monteith data on the ordinate as shown in figure 2–18.

Use graphical or linear regression techniques to determine the slope of a line that passes through the origin of the graph. The slope of the line equals the locally calibrated crop coefficient.

In this case the value of the pan coefficient $k_p = 0.7$.

623.0204 Crop coefficients

Evapotranspiration from a cropped field is composed of transpiration from the crop and evaporation from the soil. The rate of evapotranspiration from the crop (ET_c) depends on the type of crop, stage of growth, moisture content of the surface soil, and the amount of energy available to evaporate water. The reference crop evapotranspiration rate (ET_o) is used to represent a baseline rate of evapotranspiration for a clipped grass. The evapotranspiration for other crops is computed relative to the reference crop evapotranspiration. The factor that relates actual crop water use to reference crop evapotranspiration is called the crop coefficient (K_c). This section provides data to compute crop coefficients for many types of crops. It details how to adjust the crop coefficient for water stress, for increased evaporation from the soil following rain or irrigation, and for variations in the rate of crop growth.

(a) Fundamental concepts

Crop water use (ET_c) is computed using the reference crop evapotranspiration (ET_o) and a crop coefficient (K_c):

$$ET_c = K_c ET_o \qquad [2–55]$$

The value of the crop coefficient depends on several factors.

(1) Factors affecting crop coefficients

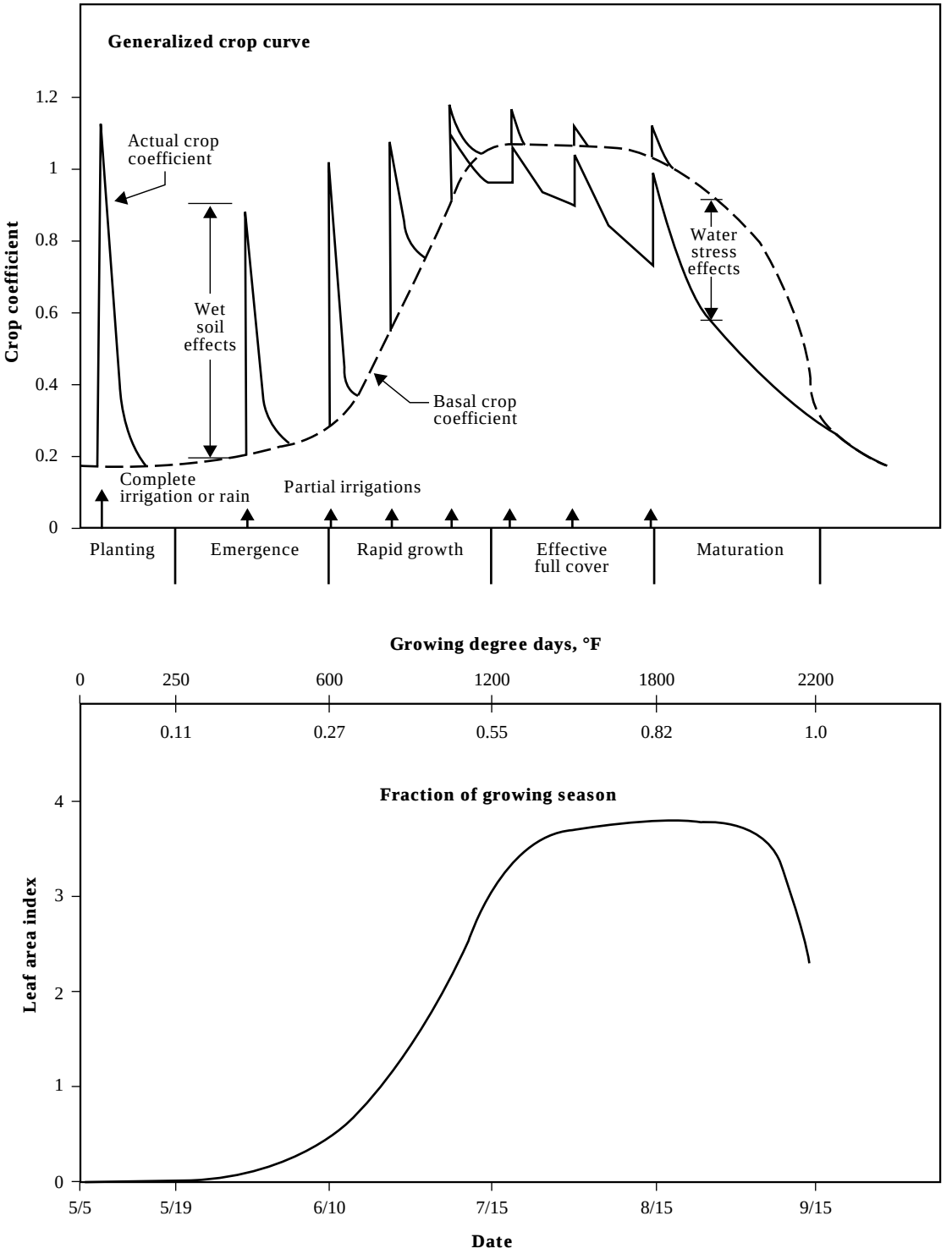
The crop coefficient depends on the growth and development of the crop canopy. The leaf area index (LAI) has been used to describe the development of the crop canopy. The LAI is the ratio of the amount of leaf area relative to the underlying land area. For example, if the total surface area of one side of the leaves is 2,600 square inches for a 3-foot square area of a field (i.e., 1,296 in^2), then the LAI is about 2. As the crop grows, the LAI increases from zero to a maximum value. The maximum LAI for irrigated corn may reach as high as 5.0 depending on the variety and location of the field. An example of the change of LAI during the year is illustrated in the lower part of figure 2–19.

The pattern of the crop coefficient closely follows the shape of the LAI curve during the season (fig. 2–19). Early in the growing season, the crop coefficient is small for an annual crop. As the crop emerges and starts to grow, transpiration begins to make up a larger part of daily water use, thus the crop coefficient increases with canopy development. At some point the canopy develops sufficiently so that the crop coefficient reaches a maximum value. This time is referred to as the effective cover date. After effective cover, the crop coefficient is generally constant for a period of time even though the plant canopy continues to increase. The crop coefficient decreases as the crop matures and leaves begin to senesce. For crops that are harvested before senescence, the crop coefficient may remain at the peak value until harvest.

Where the plant canopy is small, the soil surface is not completely shaded and evaporation from a wet soil can contribute significantly to evapotranspiration. Where the soil surface is dry, the rate of evaporation from the soil is small. However, following a rain or irrigation, the wet soil surface provides for an increased evaporation rate. Therefore, the crop coefficient increases immediately following a rain or irrigation because of evaporation from the wet soil. As the soil dries, the crop coefficient decreases back to the rate for a dry soil surface. As the canopy expands, the crop shades the soil and absorbs energy that earlier would have been used to evaporate water from the soil. The increase in the crop coefficient resulting from wet soil surface evaporation therefore decreases as the canopy develops.

Where crops are stressed because of a lack of water, the evapotranspiration rate decreases. Processes involved in reducing evapotranspiration are very complex. For computing irrigation water requirements, the effect on ET_c can be accounted for by a decrease in the crop coefficient. The effect of the factors influencing the crop coefficient is illustrated for a hypothetical crop in figure 2–19.

Figure 2–19 Generalized basal crop coefficient showing the effects of surface wetness, water stress, and leaf area index during the growing season



To account for the factors influencing ET_c, the generalized crop coefficient in equation 2–55 can be modified to account for water stress and evaporation from a wet soil surface. The combined expression is given as:

$$ET_c = \left(K_{cb}\, K_s + K_w\right) ET_o \qquad [2–56]$$

where:
- ET_c = actual crop evapotranspiration rate
- K_{cb} = basal crop coefficient
- K_s = stress factor to reduce water use for stressed crops
- K_w = factor to account for increased evaporation from wet soils following rain or irrigation
- ET_o = evapotranspiration rate for a clipped grass reference crop

The basal crop coefficient (K_{cb}) in equation 2–56 applies for a healthy crop that does not suffer water stress and where the soil surface is dry. The K_s and K_w parameters are used to adjust for water stress and wet soil evaporation in a specific field for a given day. Methods to compute the basal crop coefficient are presented in 623.0204(b). Methods to determine the adjustment factors are presented in 623.0204(c) and 623.0204(d).

(2) Methods to describe canopy development

The crop coefficient depends on how the crop canopy develops. To compute the value of the crop coefficient, a method is needed to describe the rate of canopy development. Because every year is different, the rate of crop growth varies even for the same planting date. Thus for real-time applications, such as irrigation scheduling, methods are also needed to ensure that the predicted rate of canopy development is accurate.

Computing the crop coefficient requires the use of an independent variable to describe the rate of canopy development. The two most commonly used independent variables are the elapsed time (days) since planting and the cumulative growing degree days (sometimes called heat units) since planting. The elapsed time since planting is easier to use as the basis for crop coefficient computations. However, some of the annual variation of canopy development can be accounted for using growing degree days (heat units).

Stegman (1988) suggested the following definition for growing degree days:

$$GDD_n = \sum_{i-1}^{n} \left(T_{ai} - T_{base}\right) \qquad [2–57]$$

where:
- GDD = cumulative growing degree days on the nth day after planting
- n = total number of days since planting
- T_{ai} = average air temperature on day i (°F)
- T_{base} = base temperature at which crop photosynthesis and growth begin

The average temperature is computed as:

$$T_{ai} = \left(\frac{T_{max} + T_{min}}{2}\right)_i$$

where:
- T_{max} and T_{min} = maximum and minimum air temperature on the ith day after planting

The base temperature for computing growing degree days depends on the crop species. For example, the base temperature for some warm weather crops, such as corn, is typically 50 °F and 40 °F for some cool season crops, such as wheat and barley. Because of local variations the base temperature for specific crops in a given location should be determined from regional information.

The length of the growing season for a crop depends on the location and crop variety. A method is needed to characterize the relationship between crop development and either the elapsed time or the cumulative growing degree days since planting. The fraction of the growing season procedure of Stegman (1988) can be used to normalize the length of the crop growing season. Stegman defined the fraction of the growing season for a day to be the ratio of the elapsed time (or growing degree days) since planting for the day to the amount of time (or growing degree days) required for the crop to reach maturity. For example, in figure 2–19 growing degree days were used as the independent variable to describe the crop coefficient. In the example 2,200 growing degree days after planting were needed to reach maturity. If 1,200 growing degree days had accumulated by July 15, the fraction of the growing season (F_S) on July 15 would be 1,200/2,200 or

0.55. A different variety of the same crop might only require 2,000 growing degree days to reach maturity. Thus if planted at the same time, the fraction of the growing season on July 15 would be 0.6 for the second variety. Using the fraction of the growing season as the independent variable, a single curve can be used to describe the basal crop coefficient for a type of crop. This procedure is illustrated in 623.0204(b).

For applications where irrigation requirements are computed throughout the growing season, such as irrigation scheduling, it is necessary to determine if the predicted rate of canopy development is accurate. Crops progress through specific stages of growth as they mature. These stages are easy to observe in the field. The growth stage can be related to either the elapsed time or cumulative growing degree days since planting. By observing actual growth stages, you can adjust the amount of time or growing degree days required for maturity. This allows the irrigator to adjust the crop coefficient to match actual crop development throughout the growing season. This process is illustrated in section 623.0204(f).

Many classic references on crop growth stage provide good insight in the development of localized crop coefficients. These references are available in the libraries of Land Grant Universities and many irrigation and agronomy research scientists.

(b) Determining basal crop coefficients

The crop coefficient system developed by Doorenbos and Pruitt (1977) and modified by Howell et al. (1986), will be used in this section to estimate actual crop evapotranspiration. The crop coefficients are to be used with the grass reference crop evapotranspiration methods described in section 623.0203. The crop coefficients are basal coefficients in that they represent water use of a healthy, well-watered crop where the soil surface is dry. The fraction of the growing season method developed by Stegman (1988) will be used to describe canopy development.

To use the method of Doorenbos and Pruitt (1977), the growing season is divided into four stages:

- *Initial*—Period from planting through early growth when the soil is not, or is hardly, covered by the crop (ground cover <10%).
- *Canopy development*—Period from initial stage to the time that the crop effectively covers the soil surface (ground cover @ 70 to 80%).
- *Mid-season*—Period from full cover until the start of maturation when leaves begin to change color or senesce.
- *Maturation*—Period from end of mid-season until physiological maturity or harvest.

The progression of the basal crop coefficient during the season is illustrated in figure 2–20 for corn at the example site. During the initial stage, the primary water loss is because of evaporation from the soil. Since the basal curve represents a dry soil surface, it is constant during this period. Wright (1982) suggests that the basal crop coefficient for visually dry soil is about 0.25 for grass reference crops, which is the same value recommended by Howell, et al. (1986). Wright (1982) points out that the basal coefficient could drop to about 0.1 following tillage. However, because tillage is rare following planting and before significant plant growth, a basal crop coefficient during the initial stage will be assumed to be about 0.25.

To compute the crop coefficient during other periods of crop development, four points on the crop coefficient curve need to be defined. The first point is the fraction of the growing season where canopy development begins (point 1 in fig. 2–20). At this point, the value of K_{cb} (0.25) is known based on the assumption in the preceding paragraph, so only F_{S1} is needed.

The second point occurs when the canopy has developed adequately to provide effective cover. At this time, the basal crop coefficient reaches its peak value. Thus, for the second point (point 2 in fig. 2–20), both the peak values of K_{cb} (K_{cp}) and F_{S2} are needed.

Point 3 in figure 2–20 is the time when the crop begins to mature. The only value needed for the third point is the time (F_{S3}) because the crop coefficient at point 3 equals the peak value of the basal crop coefficient.

Two locations are shown in figure 2–20 for the fourth point. The lower location represents crops that begin to senescence before harvest. To define this point, the value of the basal crop coefficient at maturity (K_{cm}) must be known. If the crop is harvested before the plant begins to mature, the crop coefficient remains constant at the peak value until harvest (see the second location of point 4 in fig. 2–20).

The five definitions needed to compute the crop coefficient (F_{S1}, F_{S2}, F_{S3}, K_{cp}, K_{cm}) are labelled in figure 2–20. The values of the parameters in figure 2–20 are F_{S1}=0.17, F_{S2}=0.45, F_{S3}=0.78, K_{cp}= 1.2, and K_{cm}=0.6. The procedure to compute the basal crop coefficient for any stage of growth is diagrammed in figure 2–21. Example 2–15 illustrates the use of the flow chart in figure 2–21 for the crop coefficients in figure 2–20.

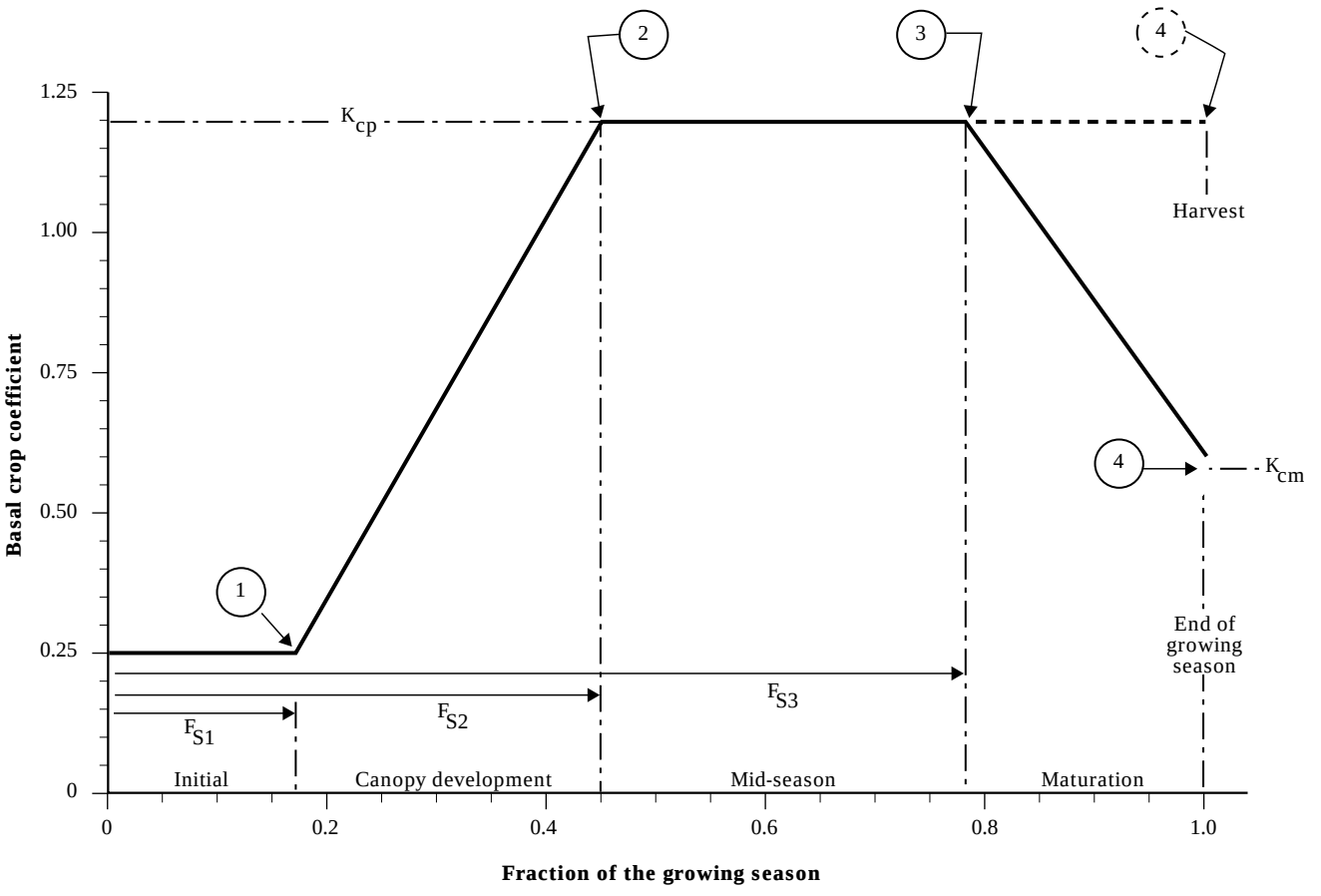
Crop coefficient value depends upon prevailing climatic conditions. Evapotranspiration of tall crops is generally affected more by wind than that of short crops, such as a grass cover crop. This effect is enhanced in arid climates. Therefore, Doorenbos and Pruitt (1977) recommend that the crop coefficient be adjusted based upon wind and humidity. Four conditions are defined for that purpose:

- moderate winds (wind run < 250 mi/d)
- strong winds (wind run > 250 mi/d)
- arid or humid climates (<20% and >70% minimum relative humidity)

The humidity range by Doorenbos and Pruitt is discontinuous. Where the mean minimum humidity is more than 20 percent or less than 70 percent, the crop coefficient value can be interpolated from the given data. The climatic data used to adjust the crop coefficient are average values for a region, not daily measured values.

Crop coefficient data have been grouped according to general crop types, and representative crop coefficient data for typical conditions are presented later in this chapter. Local crop coefficients should be used where such data are available. They need to be developed using computed clipped grass ET_o as the reference. Local crop development rates should be used in all cases because large variations in crop development occur with changing climates and crop varieties.

Figure 2–20 Basal crop coefficient for corn grown for grain in a windy and arid environment



Example 2–15 Basal crop coefficient

Given: Corn grown for grain is planted on May 1 and reaches maturity on September 20. Use the crop coefficient curve given in figure 2–20.

Required: Compute the value of the basal crop coefficient on May 15, June 15, July 15, August 15, and September 15. Use the elapsed time since planting as the basis for describing canopy development.

Solution: Determine the length of the growing season from planting to maturity:

31 days in May
30 days in June
31 days in July
31 days in August
20 days in September
143 day growing season

Determine the fraction of growing season corresponding to each date:

Date	Elapsed time since planting	Fraction of the growing season (F_s)
May 15	15	15/143 = 0.10
June 15	46	46/143 = 0.32
July 15	76	76/143 = 0.53
August 15	105	105/143 = 0.73
September 15	138	138/143 = 0.97

From figure 2–20 F_{S1}= 0.17, F_{S2}=0.45, F_{S3}=0.78, K_{cp}=1.20 and K_{cm}=0.60.

On May 15: F_S = 0.1, which is between 0 and F_{S1}, so K_{cb} = 0.25

On June 15: F_S = 0.32, which is between F_{S1} and F_{S2} so

$$K_{cb} = 0.25 + \left(K_{cp} - 0.25\right)\left(\frac{F_S - F_{S1}}{F_{S2} - F_{S1}}\right)$$

$$K_{cb} = 0.25 + (1.20 - 0.25) \times \left(\frac{0.32 - 0.17}{0.45 - 0.17}\right)$$

$$K_{cb} = 0.76$$

On July 15: F_S = 0.53, which is between F_{S2} and F_{S3}, so K_{cb} = K_{cp} = 1.20

On August 15: F_S = 0.73, which is between F_{S2} and F_{S3}, so K_{cb} = K_{cp} = 1.20

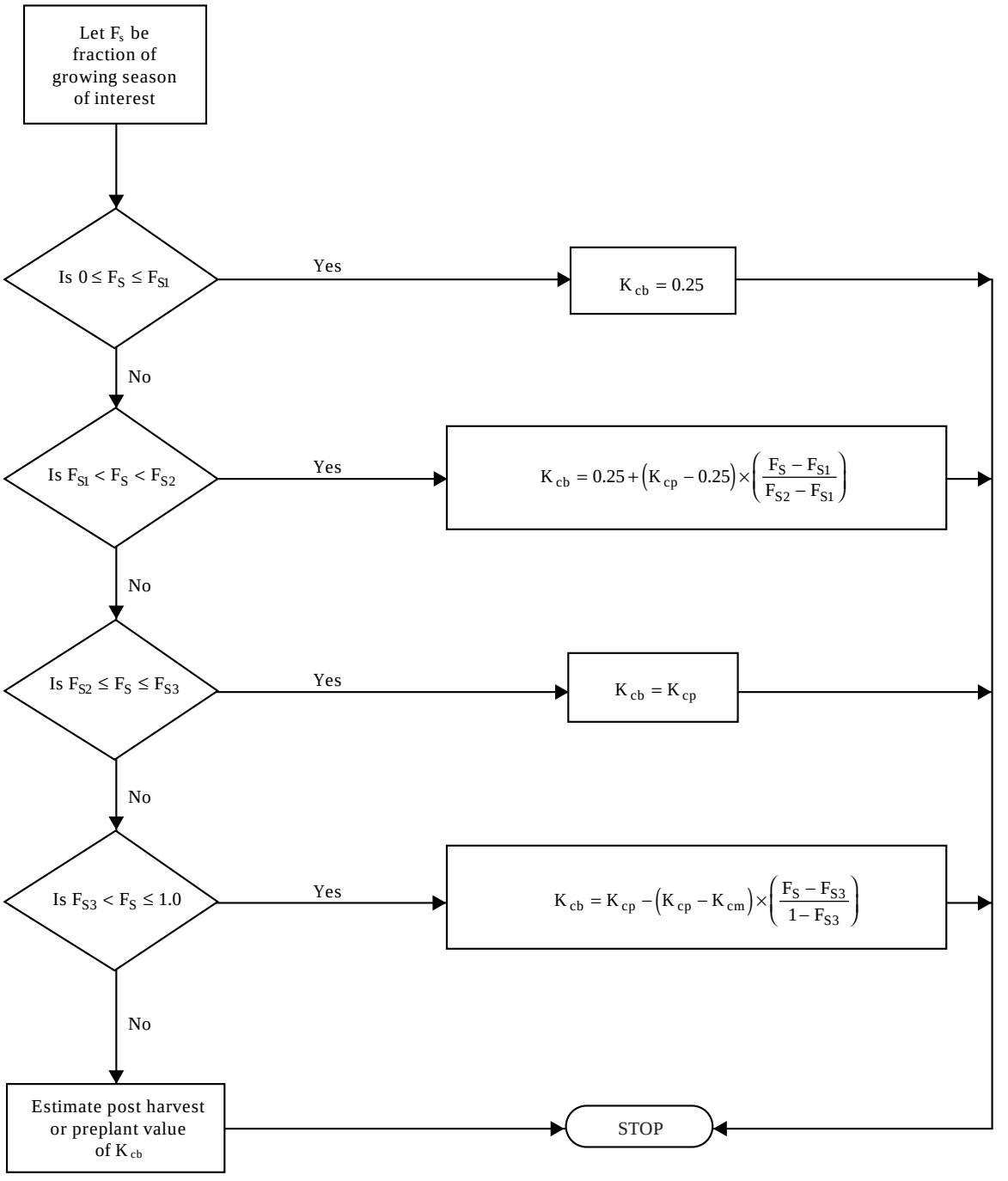
On September 15: F_S = 0.97, which is between F_{S3} and 1.0 so

$$K_{cb} = K_{cp} - \left(K_{cp} - K_{cm}\right)\left(\frac{F_S - F_{S3}}{1 - F_{S3}}\right)$$

$$K_{cb} = 1.20 - (1.20 - 0.6) \times \left(\frac{0.97 - 0.78}{1.0 - 0.78}\right)$$

$$K_{cb} = 0.68$$

Figure 2–21 Process to compute basal crop coefficients



(1) Field crops

Values for the five parameters needed to compute the basal crop coefficients for field and vegetable crops are summarized in table 2–20. Doorenbos and Pruitt (1977) stress that "crop coefficient values relate to evapotranspiration of a disease-free crop grown in large fields under optimum soil water and fertility conditions and achieving full production under the given growing environment." Crops that do not meet these provisions generally use less water unless they are raised in small fields where the effects of field boundaries can cause evapotranspiration rates to be significantly higher. Local judgment must be used.

Table 2–20 Basal crop coefficient parameters for field and vegetable crops for a grass reference crop (adapted from Doorenbos and Pruitt 1977) [2/]

Climatic conditions

Climate	Minimum relative humidity	Wind condition	Wind run (mi/d)
Arid	< 20 %	Moderate	< 250
Humid	> 70 %	Strong	> 250

Crop	Climate	Crop coefficients: Moderate wind K_{cp}	Moderate wind K_{cm}	Strong wind K_{cp}	Strong wind K_{cm}	Fractions of season for start of stages: F_{S1}	F_{S2}	F_{S3}	Days from planting until maturity
Artichoke	Humid:	0.95	0.90	0.95	0.90	0.10	0.20	0.90	310-360
	Arid:	1.00	0.95	1.05	1.00				
Barley	Humid:	1.05	0.25	1.10	0.25	0.13	0.33	0.75	120-150
	Arid:	1.15	0.20	1.20	0.20				
Beans, green	Humid:	0.95	0.85	0.95	0.85	0.22	0.56	0.89	70-90
	Arid:	1.00	0.90	1.05	0.90				
Beans, dry	Humid:	1.05	0.30	1.10	0.30	0.16	0.42	0.80	90-110
	Arid:	1.15	0.25	1.20	0.25				
Beets, table	Humid:	1.00	0.90	1.00	0.90	0.25	0.60	0.88	70-90
	Arid:	1.05	0.95	1.10	1.00				
Carrots	Humid:	1.00	0.70	1.05	0.75	0.20	0.50	0.83	100-150
	Arid:	1.10	0.80	1.15	0.85				
Castorbeans	Humid:	1.05	0.50	1.10	0.50	0.14	0.36	0.72	160-180
	Arid:	1.15	0.50	1.20	0.50				

See footnote at end of table.

Table 2–20 Basal crop coefficient parameters for field and vegetable crops for a grass reference crop (adapted from Doorenbos and Pruitt 1977)—Continued

Crop	Climate	Crop coefficients				Fractions of season for start of stages			Days from planting until maturity
		Moderate wind		Strong wind					
		K_{cp}	K_{cm}	K_{cp}	K_{cm}	F_{S1}	F_{S2}	F_{S3}	
Celery	Humid:	1.00	0.90	1.05	0.95	0.15	0.40	0.89	120-210
	Arid:	1.10	1.00	1.15	1.05				
Corn, sweet	Humid:	1.05	0.95	1.10	1.00	0.22	0.56	0.89	80-110
	Arid:	1.15	1.05	1.20	1.10				
Corn, grain	Humid:	1.05	0.55	1.10	0.55	0.17	0.45	0.78	105-180
	Arid:	1.15	0.60	1.20	0.60				
Cotton	Humid:	1.05	0.65	1.15	0.65	0.15	0.43	0.75	180-195
	Arid:	1.20	0.65	1.25	0.70				
Crucifers:	Humid:	0.95	0.80	1.00	0.85	spring planting:			80-190
brussels,	Arid:	1.05	0.90	1.10	0.95	0.18	0.63	0.89	
cabbage,									
broccoli,						autumn planting:			
cauliflower						0.15	0.33	0.79	
Cucumber:	Humid:	0.90	0.70	0.90	0.70	0.19	0.47	0.85	100-130
fresh market	Arid:	0.95	0.75	1.00	0.80				
Cucumber:	Humid:	0.90	0.85	0.90	0.85	0.19	0.47	0.85	90-120
mach. harvest	Arid:	0.95	0.95	1.00	1.00				
Eggplant	Humid:	0.95	0.80	1.00	0.85	0.22	0.54	0.84	130-140
	Arid:	1.05	0.85	1.10	0.90				
Flax	Humid:	1.00	0.25	1.05	0.25	0.15	0.36	0.75	150-220
	Arid:	1.10	0.20	1.15	0.20				
Grain, small	Humid:	1.05	0.30	1.10	0.30	0.15	0.35	0.75	150-165
	Arid:	1.15	0.25	1.20	0.25				
Lentil	Humid:	1.05	0.30	1.10	0.30	0.15	0.35	0.75	150-170
	Arid:	1.15	0.25	1.20	0.25				
Lettuce	Humid:	0.95	0.90	0.95	0.90	0.26	0.63	0.90	70-140
	Arid:	1.00	0.90	1.05	1.00				
Melons	Humid:	1.10	0.65	1.10	0.65	0.20	0.50	0.85	120-160
	Arid:	1.15	0.75	1.20	0.75				

See footnote at end of table.

Table 2–20 Basal crop coefficient parameters for field and vegetable crops for a grass reference crop (adapted from Doorenbos and Pruitt 1977)—Continued

Crop	Climate	Crop coefficients				Fractions of season for start of stages			Days from planting until maturity
		Moderate wind		Strong wind					
		K_{cp}	K_{cm}	K_{cp}	K_{cm}	F_{S1}	F_{S2}	F_{S3}	
Millet	Humid:	1.00	0.30	1.05	0.30	0.15	0.36	0.75	105-140
	Arid:	1.10	0.25	1.15	0.25				
Oats	Humid:	1.05	0.25	1.10	0.25	0.13	0.33	0.75	120-150
	Arid:	1.15	0.20	1.20	0.20				
Onion, dry	Humid:	0.95	0.75	0.95	0.75	0.10	0.26	0.75	150-210
	Arid:	1.05	0.80	1.10	0.85				
Onion, green	Humid:	0.95	0.95	0.95	0.95	0.28	0.74	0.90	70-100
	Arid:	1.00	1.00	1.05	1.05				
Peanuts	Humid:	0.95	0.55	1.00	0.55	0.20	0.46	0.80	120-140
	Arid:	1.05	0.60	1.10	0.60				
Peas	Humid:	1.05	0.95	1.10	1.00	0.20	0.47	0.85	90-110
	Arid:	1.15	1.05	1.20	1.10				
Peppers, fresh	Humid:	0.95	0.80	1.00	0.85	0.20	0.50	0.85	120-210
	Arid:	1.05	0.85	1.10	0.90				
Potato	Humid:	1.05	0.70	1.10	0.70	0.20	0.45	0.80	100-150
	Arid:	1.15	0.75	1.20	0.75				
Radishes	Humid:	0.80	0.75	0.80	0.75	0.20	0.50	0.87	30-45
	Arid:	0.85	0.80	0.90	0.85				
Safflower	Humid:	1.05	0.25	1.10	0.25	0.17	0.45	0.80	120-190
	Arid:	1.15	0.20	1.20	0.20				
Sorghum	Humid:	1.00	0.50	1.05	0.50	0.16	0.42	0.75	110-140
	Arid:	1.10	0.55	1.15	0.55				
Soybeans	Humid:	1.00	0.45	1.05	0.45	0.15	0.37	0.81	60-150
	Arid:	1.10	0.45	1.15	0.45				
Spinach	Humid:	0.95	0.90	0.95	0.09	0.20	0.50	0.90	60-100
	Arid:	1.00	0.95	1.05	1.00				
Squash, winter or pumpkin	Humid:	0.90	0.70	0.90	0.70	0.20	0.50	0.80	90-125
	Arid:	0.95	0.75	1.00	0.80				

See footnote at end of table.

Table 2–20 Basal crop coefficient parameters for field and vegetable crops for a grass reference crop (adapted from Doorenbos and Pruitt 1977)—Continued

Crop	Climate	Crop coefficients				Fractions of season for start of stages			Days from planting until maturity
		Moderate wind		Strong wind					
		K_{cp}	K_{cm}	K_{cp}	K_{cm}	F_{S1}	F_{S2}	F_{S3}	
Squash, zucchini or crookneck	Humid:	0.90	0.70	0.90	0.70	0.25	0.60	0.85	90-125
	Arid:	0.95	0.75	1.00	0.80				
Strawberry	Humid:	0.70	0.70	0.70	0.70	0.10	0.40	1.00	150-180
	Arid:	0.80	0.80	0.85	0.85				
Sugarbeet	Humid:	1.05	0.90	1.10	0.95	0.20	0.46	0.80	160-230
	Arid:	1.15	1.00	1.20	1.00				
Sunflower	Humid:	1.05	0.40	1.10	0.40	0.17	0.45	0.80	100-130
	Arid:	1.15	0.35	1.20	0.35				
Tomato	Humid:	1.05	0.85	1.10	0.85	0.20	0.50	0.80	120-180
	Arid:	1.20	0.90	1.25	0.90				
Wheat, winter	Humid:	1.05	0.25	1.10	0.25	0.13	0.33	0.75	120-150
	Arid:	1.15	0.20	1.20	0.20				
Wheat, spring	Humid:	1.05	0.55	1.10	0.55	0.13	0.53	0.75	100-140
	Arid:	1.15	0.50	1.20	0.50				

1/ For crops not included, K_{cp}, K_{cm}, F_{s1}, F_{s2}, and F_{s3} values must be developed using local technical data and resources from universities, ARS, and SCS.

(2) Grasses and forage legumes

The recommended crop coefficient for turf grass is about 0.8 and is relatively independent of cutting. The constant value applies to well-watered turf that is adaptable to the local area. No adjustment should be made for wet soil conditions for turf grass.

Basal crop coefficients and representative conditions for various grass and forage legumes are summarized in table 2–21. Crop coefficients for harvested grass and forage legumes drop at harvest and then increase as regrowth occurs. The minimum crop coefficient after cutting is denoted by the low and the maximum coefficient after effective cover represents the peak coefficient. Regrowth normally requires about half the time between harvests to reach effective cover. The first cutting of the season generally requires longer after initial crop green-up compared to regrowth after a cutting during the season. Effective cover is often reached about half way between initial growth and the first cutting.

(3) Citrus

The basal crop coefficient for citrus assumes large, mature trees and includes different tree ground cover with clean cultivation and no weed control (table 2–22). Citrus trees are often grown in dry Mediterranean-type climates. The effect of strong winds is negligible because citrus has good transpiration control. Stomatal resistance varies with humidity and temperature. Therefore, the K_{cb} values may need to be increased by 15 to 20 percent during mid-summer in humid and cooler climates.

For young orchards with little tree ground cover, K_{cb} values assume 20 percent and 50 percent tree ground cover. With frequent rain or irrigation, values for clean cultivation will approach those for no weed control. Some studies indicate somewhat higher values, up to 10 to 15 percent for grapefruit and lemons compared with those given. Months mentioned refer to the northern hemisphere; for southern hemisphere add 6 months.

(4) Deciduous trees

The basal crop coefficients for deciduous trees are summarized in table 2–23 for various conditions. The values represent full grown trees. Adjustments should be made according to the footnotes for the table. Additionally, dates generally have a basal crop coefficient of 1.0 throughout the season.

(5) Sugarcane

Approximate basal crop coefficients for sugarcane are summarized in table 2–24. Because development rates can vary significantly, local growth rates should be used to improve predictions.

Table 2–21 Basal crop coefficients for alfalfa, clover, grass-legumes, and pastures using a grass reference crop (adapted from Doorenbos and Pruitt 1977)

Climate condition	- - - - Alfalfa 1/ - - - -		Grass for hay 2/		- Clover and - grass-legumes		- - - Pasture 3/ - -	
	Low	Peak	Low	Peak	Low	Peak	Low	Peak
Humid area – moderate wind	0.50	1.05	0.60	1.05	0.55	1.05	0.55	1.05
Arid area – moderate wind	0.40	1.15	0.55	1.10	0.55	1.15	0.50	1.10
Strong wind	0.30	1.25	0.50	1.15	0.55	1.20	0.50	1.15

1/ Effective cover (i.e., peak K_{cb}) is reached after half the period between harvests, or half the time from initial growth until harvest for the first cutting. For seed crops, K_{cb} equals the peak value until harvest following initial development.
2/ Grasses for hay reach peak K_{cb} values 7 to 10 days before harvest.
3/ Values assume good management. If the pasture is overgrazed, the low value of the basal crop coefficient may be similar to that for alfalfa. Regrowth rate depends on composition of seed mixture. If substantial amounts of grass are present, the peak value is reached in 7 to 10 days. If alfalfa and clover are predominant, regrowth occurs after about 15 days.

(6) Grapes

The basal crop coefficients for grapes with the specified conditions are given in table 2–25. Values can vary considerably based on management and production practices. Local information should be used to augment information in this table.

(7) Rice

Crop coefficient values for paddy rice grown in two locations in the United States mainland are given in table 2–26. No difference is assumed in crop coefficients between broadcast or sown and transplanted rice. The growing season differs according to variety. Therefore, the length of mid-season growth period should be adjusted using local information.

The coefficients given are for paddy or upland rice because recommended practices involve the maintenance of wet topsoil. During initial crop stage, K_{cb} may need to be reduced by 15 to 20 percent for upland rice.

(8) Other perennial crops

James, et al. (1982) presented monthly crop coefficient values for four additional crops raised in the Northwestern United States. The crop coefficient values listed in table 2–27 are for a grass reference crop. Use of these coefficients in other regions should be carefully evaluated.

(9) Summary

All crop coefficients should be considered approximate values. Local information should be used to best predict irrigation requirements. Local information is available for selected areas (Snyder, et al. 1987; Stegman 1988; and Wright 1982).

In many cases locally available crop coefficients may be referenced to alfalfa rather than grass. For such cases the alfalfa based coefficients must be increased to use with a grass based reference crop. The effect of crop height and different reference crops can be evaluated using the Penman-Monteith equation. However, the coefficients can be multiplied by 1.15 for an initial estimate. (See Jensen, et al. 1990.)

Where crop evapotranspiration rates are used in irrigation scheduling, a good record keeping system should be developed to monitor crop development. Several years of data will be very valuable in developing a data base for defining crop coefficients.

Table 2–22 Basal crop coefficients for citrus grown in predominantly dry areas with moderate wind using a grass reference crop (adapted from Doorenbos and Pruitt 1977)

Ground cover	Weed control	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Large, mature trees providing 70% tree ground cover	Clean cultivated	.75	.75	.7	.7	.7	.65	.65	.65	.65	.7	.7	.7
	No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≅ 50% tree ground cover	Clean cultivated	.65	.65	.6	.6	.6	.55	.55	.55	.55	.55	.6	.6
	No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≅ 20% tree ground cover	Clean cultivated	.55	.55	.5	.5	.5	.45	.45	.45	.45	.45	.5	.5
	No weed control	1.0	1.0	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95

Table 2–23 Basal crop coefficient for full grown deciduous fruit and nut trees using a grass reference crop (from Howell, et al. 1986)

	With ground cover crop 1/									Clean, cultivated, weed free 2/								
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Cold winter with killing frost: Ground cover starting in April																		
Apple, cherry																		
Humid, moderate wind	—	.5	.75	1.0	1.1	1.1	1.1	.85	—	—	.45	.55	.75	.85	.85	.8	.6	—
Humid, strong wind	—	.5	.75	1.1	1.2	1.2	1.15	.9	—	—	.45	.55	.8	.9	.9	.85	.65	—
Arid, moderate wind	—	.45	.85	1.15	1.25	1.25	1.2	.95	—	—	.4	.6	.85	1.0	1.0	.95	.7	—
Arid, strong wind	—	.45	.85	1.2	1.35	1.35	1.25	1.0	—	—	.4	.65	.9	1.05	1.05	1.0	.75	—
Peach, apricot, pear, plum																		
Humid, moderate wind	—	.5	.7	.9	1.0	1.0	.95	.75	—	—	.45	.5	.65	.75	.75	.7	.55	—
Humid, strong wind	—	.5	.7	1.0	1.05	1.1	1.0	.8	—	—	.45	.55	.7	.8	.8	.75	.6	—
Arid, moderate wind	—	.45	.8	1.05	1.15	1.15	1.1	.85	—	—	.4	.55	.75	.9	.9	.7	.65	—
Arid, strong wind	—	.45	.8	1.1	1.2	1.2	1.15	.9	—	—	.4	.6	.8	.95	.95	.9	.65	—
Cold winter with light frost: No dormancy in grass cover crops																		
Apple, cherry, walnut 3/																		
Humid, moderate wind	.8	.9	1.0	1.1	1.1	1.1	1.05	.85	.8	.6	.7	.8	.85	.85	.8	.8	.75	.65
Humid, strong wind	.8	.95	1.1	1.15	1.2	1.2	1.15	.9	.8	.6	.75	.85	.9	.9	.85	.8	.8	.7
Arid, moderate wind	.85	1.0	1.15	1.25	1.25	1.25	1.2	.95	.85	.5	.75	.95	1.0	1.0	.95	.9	.85	.7
Arid, strong wind	.85	1.05	1.2	1.35	1.35	1.35	1.25	1.0	.85	.5	.8	1.0	1.05	1.05	1.0	.95	.9	.75
Peach, apricot, pear, plum, almond, pecan																		
Humid, moderate wind	.8	.85	.9	1.0	1.0	1.0	.95	.8	.8	.55	.7	.75	.8	.8	.7	.7	.65	.55
Humid, strong wind	.8	.9	.95	1.0	1.1	1.1	1.0	.85	.8	.55	.7	.75	.8	.8	.8	.75	.7	.6
Arid, moderate wind	.85	.95	1.05	1.15	1.15	1.15	1.1	.9	.85	.5	.7	.85	.9	.9	.9	.8	.75	.65
Arid, strong wind	.85	1.0	1.1	1.2	1.2	1.2	1.15	.95	.85	.5	.75	.9	.95	.95	.95	.85	.8	.7

1/ For young orchards with tree ground cover of 20 and 50 percent, reduce mid-season K_{cb} values by 10 to 15 percent and 5 to 10 percent, respectively.
2/ For young orchards with tree ground cover of 20 and 50 percent, reduce mid-season K_{cb} values by 25 to 35 percent and 10 to 15 percent, respectively.
3/ For walnut, March through May possibly 10 to 20 percent lower values because of slower leaf growth.

Table 2–24 Basal crop coefficients for sugarcane using a grass reference crop (adapted from Howell, et al. 1986)

Crop age Months 12	Crop age Months 24	Growth stages	Humid Moderate wind	Humid Strong wind	Arid Moderate wind	Arid Strong wind
0-1	0-2.5	Planting to 1/4 canopy	0.55	0.60	0.40	0.45
1-2	2.5-3.5	1/4 to 1/2 canopy	0.80	0.85	0.75	0.80
2-2.5	3.5-4.5	1/2 to 3/4 canopy	0.90	0.95	0.95	1.00
2.5-4	4.5-6	3/4 to full canopy	1.00	1.10	1.10	1.20
4-10	6-17	Peak use	1.05	1.15	1.25	1.30
10-11	17-22	Early senescence	0.80	0.85	0.95	1.05
11-12	22-24	Ripening	0.60	0.65	0.70	0.75

Table 2–25 Basal crop coefficients for grapes with clean cultivation, infrequent irrigation, and dry soil surface most of the season using a grass reference crop (adapted from Howell, et al. 1986)

Conditions 1/	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Mature grapes grown in areas of killing frost, initial leaves early May, harvest mid-September, ground cover 40 to 50 percent at mid-season									
1	——	——	0.50	0.65	0.75	0.80	0.75	0.65	——
2	——	——	0.50	0.70	0.80	0.85	0.80	0.70	——
3	——	——	0.45	0.70	0.85	0.90	0.80	0.70	——
4	——	——	0.50	0.75	0.90	0.95	0.90	0.75	——
Mature grapes grown in areas of only light frost, initial leaves early April, harvest late August to early September, ground cover 30 to 35 percent at mid-season									
1	——	0.50	0.55	0.60	0.60	0.60	0.60	0.50	0.40
2	——	0.50	0.55	0.65	0.65	0.65	0.65	0.55	0.40
3	——	0.45	0.60	0.70	0.70	0.70	0.70	0.60	0.35
4	——	0.45	0.65	0.75	0.75	0.75	0.75	0.65	0.35
Mature grapes grown in hot dry areas, initial leaves late February to early March, harvest late half of July, ground cover 30 to 35 percent at mid-season 2/									
3	0.25	0.45	0.60	0.70	0.70	0.65	0.55	0.45	0.35
4	0.25	0.45	0.65	0.75	0.75	0.70	0.55	0.45	0.35

1/ 1—humid, moderate wind
2—humid, strong wind
3—arid, moderate wind
4—arid, strong wind

2/ The K_{cb} values for the last two growing conditions must be reduced if ground cover is less than 35 percent.

Table 2–26 Crop coefficients for paddy rice grown in the United States mainland using a grass reference crop (adapted from Doorenbos and Pruitt 1977)

	Planting	Harvest	First & second month	Mid-season	Last four weeks
Wet summer (South)					
Moderate wind	May	September–	1.1	1.1	.95
Strong wind		October	1.15	1.15	1.0
Dry summer (California)					
Moderate wind	Early	Early	1.1	1.25	1.0
Strong wind	May	October	1.15	1.35	1.05

Table 2–27 Monthly crop coefficients for some perennial crops raised in Northwestern United States (values are adapted from James, et al. 1982)

Crop	Monthly crop coefficient							
	Jan–Apr	May	June	July	Aug	Sept	Oct	Nov–Dec
Hops	0.50	0.50	0.85	0.95	1.50	0.25	0.25	0.25
Mint	0.50	0.50	0.60	1.10	1.20	1.20	1.10	0.50
Raspberries	0.40	1.05	1.20	1.20	1.15	0.85	0.50	0.40
Strawberries	0.40	0.40	0.50	0.30	0.40	0.40	0.40	0.40

(c) Water stress factor

The water use by stressed crops is very complex and requires extensive information to predict. Irrigation systems are generally designed and operated to prevent stress, so the effects of stress generally are not too significant. If management or water supply limitations restrict irrigation, the effect of stress should be considered. The quality of some crops is also improved by controlled stress. In these cases, the computation of the water use is critical to ensure quality and to minimize yield reduction.

The effect of water stress on the rate of evapotranspiration can be described using the stress factor K_s, which is based on soil-water content (fig. 2–22). One method is the linear function used by Hanks (1974) and Ritchie (1973). With this method the stress factor is based on the percentage of the total available soil water that is stored in the crop root zone. The total available soil water (TAW) is the amount of water a soil can hold between the field capacity and permanent wilting point water contents. It is calculated as:

$$TAW = R_d \frac{\theta_{fc} - \theta_{pwp}}{100} \qquad [2–58]$$

where:

TAW = total available water (in)
θ_{fc} = volumetric water content at field capacity (%)
θ_{pwp} = volumetric water content at the permanent wilting point (%)
R_d = root zone depth (in)

The available water stored in the root zone is computed as:

$$AW = R_d \frac{\theta_v - \theta_{pwp}}{100} \qquad [2–59]$$

where:

AW = available soil water (in)
θ_v = current volumetric water content (%)

The percent of the total available water that is stored in the root zone equals

$$ASW = \frac{AW}{TAW} 100 \qquad [2–60]$$

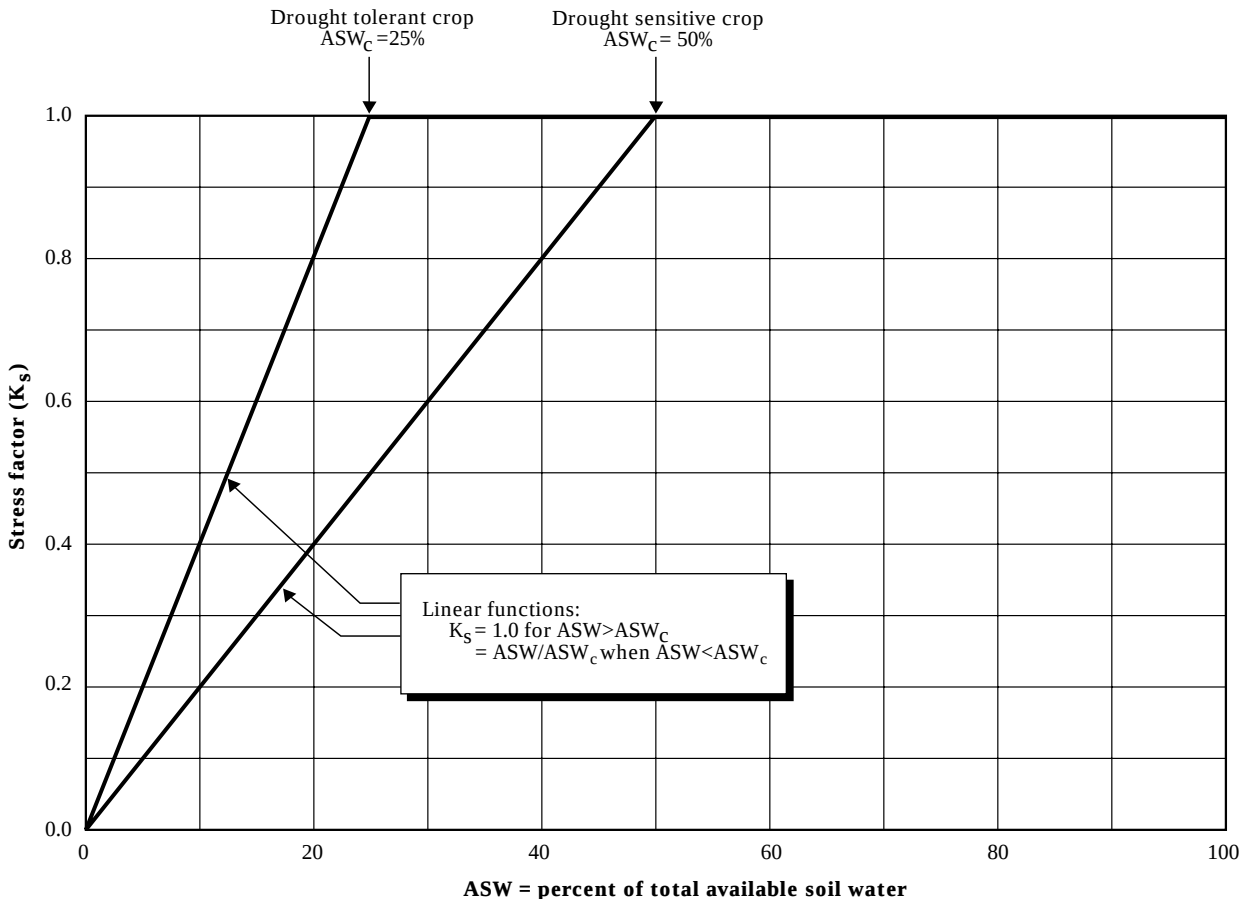
Using these definitions the stress factor K_s can be computed as:

$$K_s = \frac{ASW}{ASW_c} \quad \text{for } ASW < ASW_c$$
$$= 1.0 \qquad ASW \geq ASW_c \qquad [2–61]$$

The critical value of ASW varies depending on the drought tolerance of the crop (fig. 2–22). Crops that maintain ET_c under dry soil conditions, termed drought tolerant crops, and an average value of ASW_c = 25% can be used. For crops that are sensitive to drought the value of ASW_c should be about 50 percent. Example 2–16 illustrates the use of the stress factor in computing ET_c.

Irrigation water requirements generally are needed for conditions where the economic optimal yield is often near the maximum yield. Accordingly, irrigation management usually results in little water stress. For these conditions the stress factor has little effect on evapotranspiration predictions, and either form of equation for the stress factor is acceptable. If deficit irrigation is important, describing the effect of water stress on evapotranspiration becomes more critical. For most applications, the methods presented in figure 2–22 will be acceptable.

Figure 2–22 Functions used to reduce evapotranspiration based on soil-water content



Example 2–16 Water stress factor

Given: The volumetric water content at field capacity and the permanent wilting point are 25 and 10 percent, respectively. Soil water was measured in two fields with the following results:

Field A: Available water in the root zone = 2 inches

Field B: Available water in the root zone = 5 inches

The crop root zone is 4 feet deep in both fields. The reference crop evapotranspiration rate is 0.3 inch per day, and the basal crop coefficient is 1.1 at this time of year.

Required: Compute the evapotranspiration rate for a drought-tolerant and drought-sensitive crop in each field.

Solution:

1. Compute the total available water in the 4-foot root zone.

$$TAW = 48 \text{ in} \times \frac{(25-10)}{100} = 7.2 \text{ in}$$

2. Compute ASW for each field.

Field A: $ASW = \left(\frac{2}{7.2}\right) \times 100 = 28\%$

Field B: $ASW = \left(\frac{5}{7.2}\right) \times 100 = 69\%$

3. Compute the ET_c for a drought-tolerant crop on each field. For this case ASW_c = 25%

Because ASW > ASW_c for both Field A and B, the value of K_s = 1.0 for both fields.

The evapotranspiration rate is then

$$ET_c = K_{cb} K_s ET_o = 1.1 \times 1.0 \times 0.3 = 0.33 \text{ in / d}$$

4. Compute the ET_c for the drought-sensitive crop on both fields.
For drought-sensitive crops, the value of ASW_c = 50 percent; thus the value of the stress factor for each field is:

Field A: ASW = 28%, which is less than ASW_c — so

$$K_s = \frac{ASW}{ASW_c} = \frac{28\%}{50\%} = 0.56$$

$$ET_c = K_{cb} K_s ET_o = 1.1 \times 0.56 \times 0.33 = 0.18 \text{ in / d}$$

Field B: ASW = 69%, which is more than ASW_c — so

K_s = 1.0, and the value for ET_c is the same as that for the drought-tolerant crop = 0.33 in/d.

(d) Wet soil evaporation

The increased rate of evaporation because of a wet soil surface is influenced by the amount of canopy development, the energy available to evaporate water and the hydraulic properties of the soil. One of the most widely cited methods to predict this effect is by Ritchie (1972). That method depends on knowing the leaf area index of the crop and soil parameters that are not readily available. Therefore, such models have not been widely used to estimate irrigation requirements. Instead, simpler methods have been developed.

The wet soil evaporation factor (K_w) was described by Wright (1981) using a relationship similar to:

$$K_w = F_w\left(1 - K_{cb}\right)f\left(t\right) \qquad [2–62]$$

where:

F_w = the fraction of the soil surface wetted

$f(t)$ = wet soil surface evaporation decay function

$$= 1 - \sqrt{\frac{t}{t_d}}$$

t = elapsed time since wetting, days

t_d = days required for the soil surface to dry

The wet soil surface evaporation adjustment is only used as long as the basal crop coefficient (K_{cb}) is less than one.

The fraction of the soil surface wetted depends on the amount and method of irrigation. Suggested values for various methods of watering are summarized in table 2–28. Values for F_w can be estimated for actual conditions by observing soil conditions following an irrigation.

The amount of time required for the soil surface to dry depends on the soil texture. The value of t_d also depends on the evaporative demand of the climate. When the ET_o is high, the length of time for drying will be short. During cool, cloudy, and damp periods, soil evaporation might persist longer. An approximate drying time is given in table 2–29 for six soils, and the value of the wet soil surface decay factor is also summarized. This method can easily be calibrated to local conditions by observing the drying time required for actual soil conditions.

The amount of excess evaporation from a wet soil is limited by the amount of water received by rain or irrigation. If equation 2–58 is used indiscriminately, the amount of wet soil evaporation could exceed the water received. Hill, et al. (1983) developed a term called the wet soil persistence factor (P_f) to account for this possibility. The persistence factor represents the cumulative effect of wet soil surface evaporation. The total wet soil evaporation from a wetting event (E_{ws}) can be estimated as:

$$E_{ws} = P_f F_w\left[1 - \overline{K_{cb}}\right]\overline{ET_o} \qquad [2–63]$$

where:

$\overline{K_{cb}}$ = the average basal crop coefficient during the drying period

$\overline{ET_o}$ = the average daily reference crop evapotranspiration during the drying period

The maximum possible value for E_{ws} is the amount of irrigation or rain water received.

Example 2–17 helps explain the procedure for estimating the wet soil surface evaporation. This example illustrates that the persistence factor only approximates the cumulative daily evaporation because of daily variations.

Table 2–28 Fraction of the soil surface wetted for various types of irrigation

Method	F_w
Rain	1.0
Above canopy sprinklers	1.0
LEPA systems (every other row)	0.5
Borders and basin irrigation	1.0
Furrow irrigation	
Large application depth	1.0
Small application depth	0.5
Every other row irrigated	0.5
Trickle irrigation	0.25

Table 2–29 Wet soil surface evaporation decay function f(t) [1/] and the persistence factor P_f [2/] for typical soils (adapted from Hill, et al. 1983)

Time since wetting (t), days [3/]	Clay	Clay loam	Silt loam	Sandy loam	Loamy sand	Sand
	Drying time (t_d), days					
	10	7	5	4	3	2
0	1.00	1.00	1.00	1.00	1.00	1.00
1	0.68	0.62	0.55	0.50	0.42	0.29
2	0.55	0.47	0.37	0.29	0.18	0.00
3	0.45	0.35	0.23	0.13	0.00	
4	0.37	0.24	0.11	0.00		
5	0.29	0.15	0.00			
6	0.23	0.07				
7	0.16	0.00				
8	0.11					
9	0.05					
10	0.00					
P_f	3.89	2.90	2.26	1.92	1.60	1.29

1/ f(t) = wet soil evaporation decay function = $1 - \sqrt{\frac{t}{t_d}}$

2/ P_f = wet soil persistence factor = $\sum_{t=0}^{t_d} f(t)$

3/ t = 0 represents the day of wetting, and 1 is one day after wetting.

Example 2–17 Wet soil surface evaporation

Given: 0.5 inches applied with a LEPA (Low Energy Precision Application) irrigation system on day 0. Fine sandy loam soil and the following daily climatic and crop coefficient data.

Day	K_{cb}	ET_o (in/da)
0	0.40	0.25
1	0.42	0.30
2	0.44	0.28
3	0.46	0.40
4	0.48	0.35
5	0.50	0.20

Required: Determine the daily wet soil evaporation rate and the total wet soil evaporation for the event.

Solution: $K_w = F_w [1 - K_{cb}] f(t)$

Using table 2–28, $F_w = 0.5$.

Using table 2–29, the daily wet soil evaporation can be computed.
The daily $E_{ws} = K_w ET_o$

Day	f(t)	K_s	Daily E_{ws}
0	1.00	0.30	0.075
1	0.50	0.15	0.045
2	0.29	0.08	0.022
3	0.13	0.03	0.012
4	0.00	0.00	0.000
5	0.00	0.00	0.000
		Total	0.15

The persistence factor P_f for the fine sandy loam soil is 1.92.
The cumulative wet soil evaporation can be estimated using equation 2–63:

$$E_{ws} = P_f F_w \left(1 - \overline{K_{cb}}\right) \overline{ET_c}$$

For the four days of wet soil evaporation,

$$\overline{K_{cb}} = 0.43 \text{ and } \overline{ET_o} = 0.31 \text{ in / d}$$

Thus, $E_{ws} \cong (1.92)(0.5)(1 - 0.43)(0.31) = 0.17$ in

Since E_{ws} is ≤ 0.5 inches, results are acceptable.

(e) Average crop coefficients

A daily accounting of field conditions is impractical for some irrigation management decisions. The stress factor used in equation 2–56 requires that the soil-water content be known on a daily basis, which leads to excessive calculations when computing crop evapotranspiration for long periods. To avoid excessive calculations, an average crop coefficient for a period is generally used. The average crop coefficient must include the basal crop coefficient and the effect of wet soil evaporation. If water stress is expected, an appropriate stress factor can also be selected although this is generally not done. The average crop coefficient (K_a) is defined as:

$$K_a = \overline{K_s}\,\overline{K_{cb}} + \overline{K_w} \qquad [2–64]$$

where:

$\overline{}$ denotes the average value of each parameter over the calculation period.

To estimate the average crop coefficient, the wet soil surface evaporation must be estimated. This can be done using a rainfall recurrence interval. The recurrence interval is the average time between wetting events. For example, if the recurrence interval is 7 days, one irrigation or rain could be expected each week. The average wet soil surface factor can be estimated by:

$$\overline{K_w} = F_w\left(1 - \overline{K_{cb}}\right)A_f \qquad [2–65]$$

where

A_f = the average wet soil evaporation factor that is listed in table 2–30. Using this approach, the average crop coefficient can be computed as:

$$K_a = \overline{K_s}\,\overline{K_{cb}} + F_w\left(1 - \overline{K_{cb}}\right)A_f \qquad [2–66]$$

Example 2–18 helps illustrate the procedure.

Table 2–30 Average wet soil evaporation factor (A_f)

Recurrence interval (days)	Clay	Clay loam	Silt loam	Sandy loam	Loamy sand	Sand
1	1.000	1.000	1.000	1.000	1.000	1.000
2	0.842	0.811	0.776	0.750	0.711	0.646
3	0.746	0.696	0.640	0.598	0.535	0.431
4	0.672	0.608	0.536	0.482	0.402	0.323
5	0.611	0.535	0.450	0.385	0.321	0.259
6	0.558	0.472	0.375	0.321	0.268	0.215
7	0.511	0.415	0.322	0.275	0.229	0.185
8	0.467	0.363	0.281	0.241	0.201	0.162
9	0.427	0.323	0.250	0.214	0.178	0.144
10	0.389	0.291	0.225	0.193	0.161	0.129
11	0.354	0.264	0.205	0.175	0.146	0.118
12	0.325	0.242	0.188	0.161	0.134	0.108
13	0.300	0.224	0.173	0.148	0.124	0.099
14	0.278	0.208	0.161	0.138	0.115	0.092
15	0.260	0.194	0.150	0.128	0.107	0.086
16	0.243	0.182	0.141	0.120	0.100	0.081
17	0.229	0.171	0.132	0.113	0.094	0.076
18	0.216	0.161	0.125	0.107	0.089	0.072
19	0.205	0.153	0.118	0.101	0.085	0.068
20	0.195	0.145	0.113	0.096	0.080	0.065
21	0.185	0.138	0.107	0.092	0.076	0.062
22	0.177	0.132	0.102	0.088	0.073	0.059
23	0.169	0.126	0.098	0.084	0.070	0.056
24	0.162	0.121	0.094	0.080	0.067	0.054
25	0.156	0.116	0.090	0.077	0.064	0.052
26	0.150	0.112	0.087	0.074	0.062	0.050
27	0.144	0.108	0.083	0.071	0.059	0.048
28	0.139	0.104	0.080	0.069	0.057	0.046
29	0.134	0.100	0.078	0.066	0.055	0.045
30	0.130	0.097	0.075	0.064	0.054	0.043

where:

$$A_f = \sum_{i=0}^{R_f - 1}\left(\frac{1 - \sqrt{\frac{i}{t_d}}}{R_f}\right)$$

R_f = recurrence interval of wetting days
t_d = drying time for the respective soil
i = days since wetting

Example 2–18 Average crop coefficient

Given: The basal crop coefficient for corn is shown in figure 2–20 for the example site.
The soil type is sandy loam. The wetting recurrence interval is 4 days during the initial and canopy development stages and 14 days during the maturation stage.
The field is irrigated with overhead sprinklers, and little crop water stress occurs.

Required: Draw the basal and average crop coefficient curves for this site if water stress is minimal.

Solution: From the available information, F_w = 1.0 and K_s = 1.0. From table 2–30 the average wet soil evaporation factor is:

Period	A_f
Initial	0.482
Canopy development	0.482
Maturation	0.138

Then select basal crop coefficients for representative fractions of the growing season and compute K_a as:

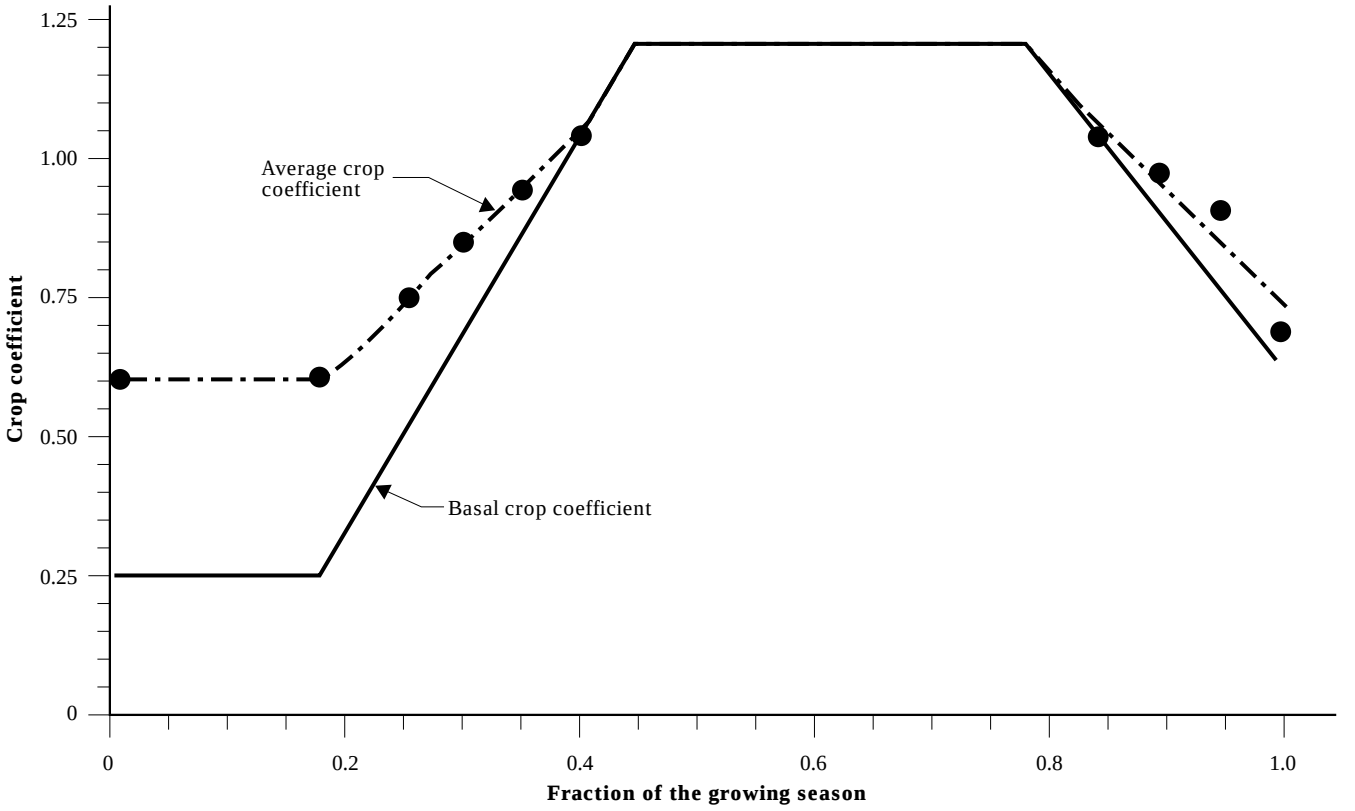
$$K_a = \overline{K_s}\,\overline{K_{cb}} + F_w\left(1 - \overline{K_{cb}}\right)A_f$$

Fraction of growing season	A_f	K_{cb}	K_a
0.00	0.482	0.25	0.61
0.17	0.482	0.25	0.61
0.25	0.482	0.52	0.75
0.30	0.482	0.69	0.84
0.35	0.482	0.86	0.93
0.40	0.482	1.03	1.03
0.85	0.138	1.01	1.01
0.90	0.138	0.94	0.95
0.95	0.138	0.84	0.86
1.00	0.138	0.60	0.66

Note that no adjustment is made for wet soil evaporation when K_{cb} is > 1.0.

The basal and average crop coefficient curves are plotted in figure 2–23.

Figure 2–23 Comparison of basal and average crop coefficients for the average crop coefficient example



(f) Estimating evaporation during the nongrowing season

Sometimes it is necessary to compute water use for the time between when a crop matures, or is harvested, and when the next crop is planted. This time period is called the nongrowing season. In some locations this is a long period. For example, in the Midwest row crops generally mature in September and are harvested in September or October. The next crop is usually planted in April or May. This leaves 6 months during the fall, winter, and spring for evaporation. The evaporation of water from soils during this time can be significant for annual water budgets and water allocation considerations.

Doorenbos and Pruitt (1977) presented a method to compute an average crop coefficient for the nongrowing season. Their method depends on the frequency of rain and the reference crop evapotranspiration during the time interval of concern:

when f_p <4 days: (2–67)

$$K_a = \left(1.286 - 0.27\ f_p\right) EXP\left\{\left[0.254 - 1.07\ LN\left(f_p\right)\right] ET_o\right\}$$

when $f_p \geq 4$ days:

$$K_a = 2\left(f_p\right)^{-0.49} EXP\left\{\left[-0.51 - 1.02\ LN\left(f_p\right)\right] ET_o\right\}$$

where:

K_a = average crop coefficient during the period
f_p = interval between significant rains or irrigations (days)
LN = natural logarithm
ET_o = average reference crop evapotranspiration for the period (in/d)
EXP = exponential function

Once the average crop coefficient is determined, the evaporation for the nongrowing season can be computed as with other average crop coefficients. Example 2–19 illustrates the use of equation 2–67.

The method of Doorenbos and Pruitt (1977) does not apply for all conditions. It is inappropriate for frozen or snow covered soils. Evaporation during the nongrowing season is affected by several other factors. Tillage lifts wet soils to the surface, increasing the evaporation rate for several days following the tillage.

Example 2–19 Nongrowing season crop coefficient

Given: In spring a rain occurs about once per week, and the average grass reference crop evapotranspiration is about 0.15 inches per day.

Required: Compute the expected weekly evaporation for this site.

Solution: 1. Compute the average crop coefficient for the nongrowing season:
The interval between rains is 7 days, and ET_o is 0.15 inches per day, so

$$K_a = 2\left(f_p\right)^{-0.49} EXP\left\{\left[-0.51 - 1.02\ LN\left(f_p\right)\right] ET_o\right\}$$

$$K_a = 2\left(7\right)^{-0.49} EXP\left\{\left[-0.51 - 1.02\ LN\left(7\right)\right] 0.15\right\}$$

$$K_a = 0.53$$

2. Compute the average daily evaporation:

$$ET_c = K_a ET_o = 0.53 \times 0.15 = 0.08 \text{ in / d}$$

Thus the weekly evaporation = 0.56 inch per week

Tillage also reduces the amount of crop residue on the soil surface. Residue shades the soil surface and increases the resistance to vapor movement from the soil to the environment. However, Gardner (1983) showed that the daily evaporation rate for a residue-covered soil could exceed that from a bare soil after a long period of drying. Weeds and other factors can also substantially change evapotranspiration during the nongrowing season. Thus predictions of evaporation during the nongrowing period may need to be adjusted for special circumstances or events. Local information is needed to make the adjustment.

(g) Adjusting crop coefficients for real-time predictions

When predicting crop water use for real-time applications, such as irrigation scheduling, an irrigator is often faced with shifting the crop coefficient. The adjustment is necessary because actual climate conditions may vary from the expected weather, causing a crop to develop slower or faster than anticipated. Several aspects regarding this adjustment are presented in 623.0204.

Many attempts have been made to identify the proper set of parameters and relationships to predict the rate of crop development. However, those efforts have only been partly successful. One of the most common expressions is growing degree days, sometimes called heat units. Growing degree days can be computed in several ways. In many cases the methods are all equally effective, although each species may have unique characteristics that favor different procedures. Soybeans, for example, are photoperiod dependent.

The procedure in this part of chapter 2 centers on corn grown in the Midwestern United States. The procedure is generally applicable to other crops and conditions, but will require evaluation of species and local conditions. Some helpful references for such evaluations include Coelho and Dale (1980), Cross and Zuber (1972), Mederski et al. (1973), Ritchie et al. (1982), and Vanderlip (1972).

The growing degree day basis used in this section illustrates how to adjust the crop coefficient for corn given in equation 2–56. A base temperature of 50 °F was used for corn in the Midwest. Growing degree days were accumulated from emergence until physiological maturity. For perennial crops, the first growth should be used in place of emergence.

The growth of crops generally can be divided into definable stages. Hanway (1971) and Ritchie and Hanway (1982) established such a set of stages for corn (table 2–31). Either of Hanway's systems can be used although the second method is more descriptive. Observable stages need to be defined so that an irrigator can determine the current crop condition. The stages of growth can then be related to growing degree days for a season (fig. 2–24).

The relation of crop development to growing degree days in figure 2–24 shows a very good linear relationship for a single season. In fact, a linear relationship occurs for most seasons. The problem is that the linear relationship varies from year to year and by location. The linear relationships for the same variety grown in western Nebraska for 5 years and in eastern Nebraska for 2 years are shown in figure 2–25. These results clearly show the variability of the growth rate of a single variety between years and locations. The linear relationship for each year was good, but a different line was needed for each year. The major difficulty is that the number of growing degree days needed to reach maturity varies annually ranging from 2,200 to about 2,700 for the condition depicted in figure 2–25. The variability is further enhanced for different varieties (fig. 2–26).

The stages of growth can be related to the fraction of the growing season based on growing degree days (fig. 2–27). The fraction of the growing season is computed as:

$$F_S = \frac{GDD_i}{GDD_m} \qquad [2–68]$$

where:

GDD_i = cumulative growing degree days on day i

GDD_m = cumulative growing degree days needed for maturity

For example, using data from figure 2–24, the fraction of the growing season when 1,200 GDD have accumulated would be:

$$F_S = \frac{1,200}{2,314} = 0.52$$

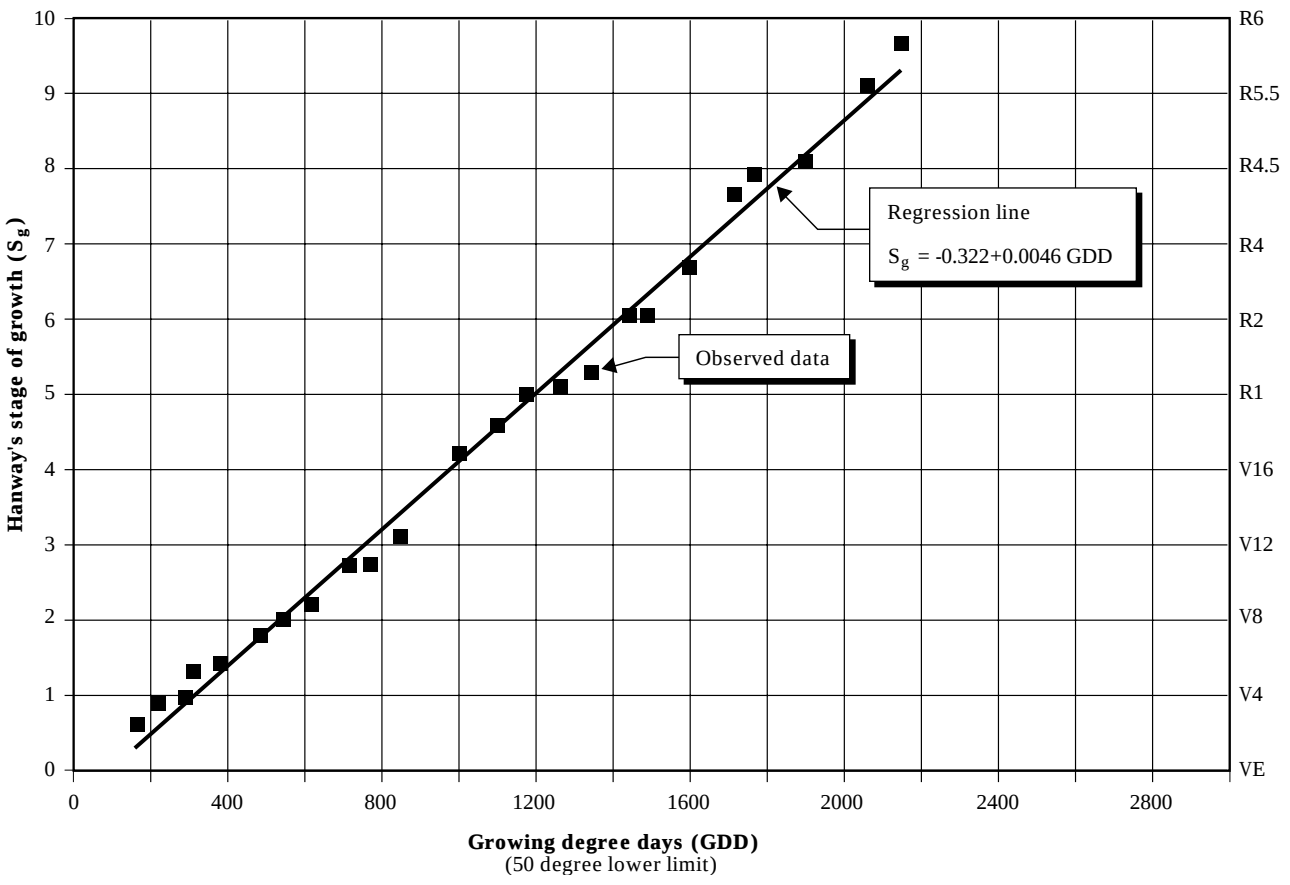
since 2,314 growing degree days were needed to reach maturity.

Table 2–31 Hanway's stages of growth for corn

Old stage [1/]	New stage [2/]	Identifying characteristics
0	VE	Plant emergence
1	V4	Collar of 4th leaf visible
2	V8	Collar of 8th leaf visible
3	V12	Collar of 12th leaf visible
4	V16	Collar of 16th leaf visible
5	R1	75% of silks visible
6	R2	Blister kernel stage
7	R4	Kernels at dough stage
8	R4.5	Beginning dent
9	R5.5	Full dent
10	R6	Physiological maturity (black layer)

1 From Hanway (1971).
2 From Ritchie and Hanway (1982).

Figure 2–24 Example of the relationship of growth stages of corn to cumulative growing degree days since emergence for western Nebraska (exact relationship depends on the year and cultivar)



The relationship given in figure 2–27 can be used to adjust crop coefficients to reflect actual crop development. The irrigator must first determine the stage of growth for the actual crop. Then the corresponding fraction of the growing season can be determined from the relationship given in figure 2–27. These data can then be used to estimate the number of growing degree days required to reach maturity for the specific season. Example 2–20 helps illustrate the procedure.

This example illustrates that an average relationship can be used along with current observations to improve real-time crop growth predictions. Generally, the procedure will work best if several years of data are available to develop figures 2–24 and 2–27.

The procedure to adjust crop coefficients to reflect actual growth is important for real-time management, such as irrigation scheduling. Unfortunately, sufficiently accurate growth information is impossible to provide in this publication for all crops and locations. Local information should be developed for accurate computations.

The methods developed in this section related crop growth to the fraction of growing season that has been used as the basis for the basal crop coefficient. This provides an integrated system for real-time management.

When long-term water requirements must be determined, or when planning for a system that does not already exist, the fraction of the growing season can be determined using average temperatures to compute growing degree days. Of course, for these situations, the crop curve would not be adjusted. For these situations, the growing degree days needed for maturity should be estimated based upon the expected maturity date if better information on crop development is not known.

Figure 2–25 Example of the relationship of crop development to growing degree days for Pioneer 3901 corn grown for 5 years in western Nebraska and 2 years in eastern Nebraska

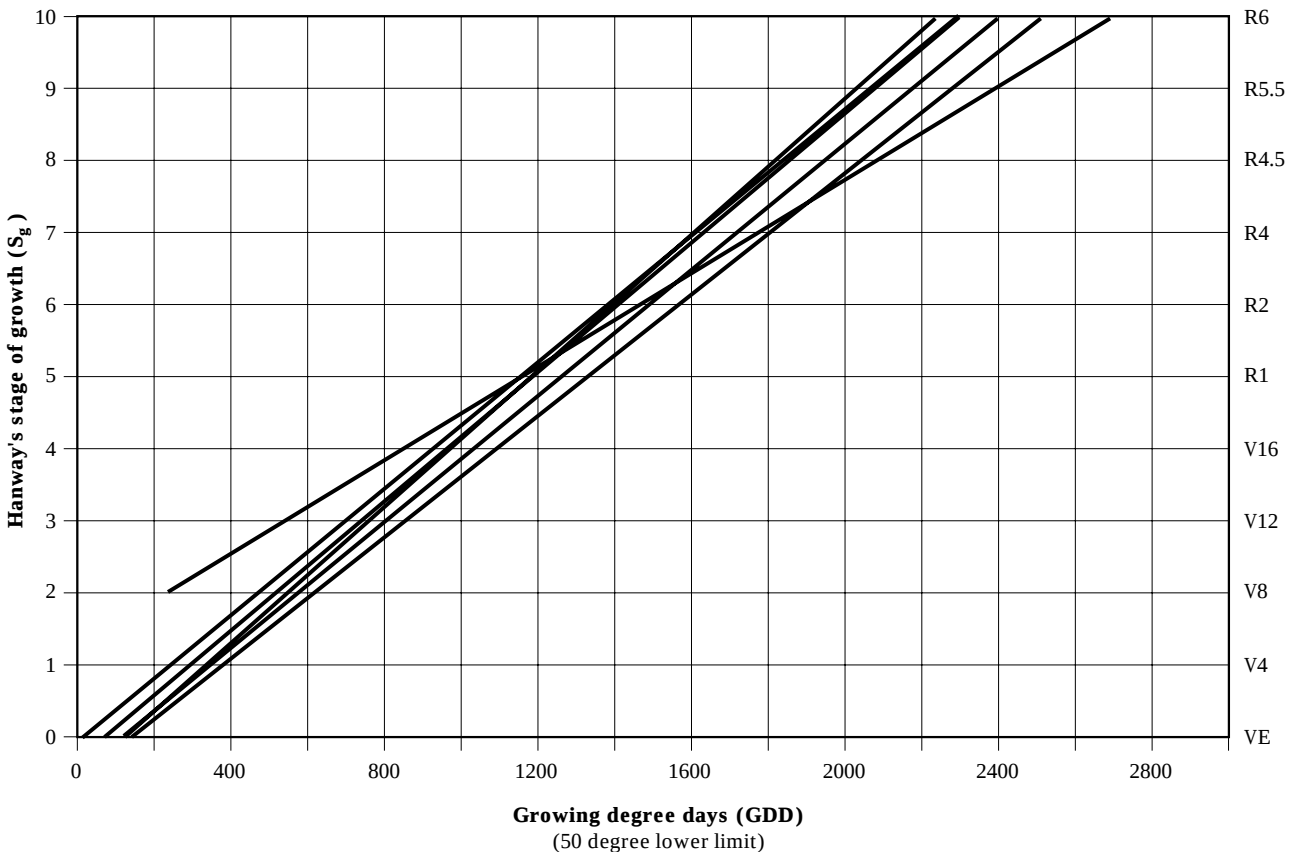


Figure 2–26 Variation of growing degree days required from emergence to maturity for six corn varieties of different maturity ratings (all varieties were grown in eastern Nebraska during the same year)

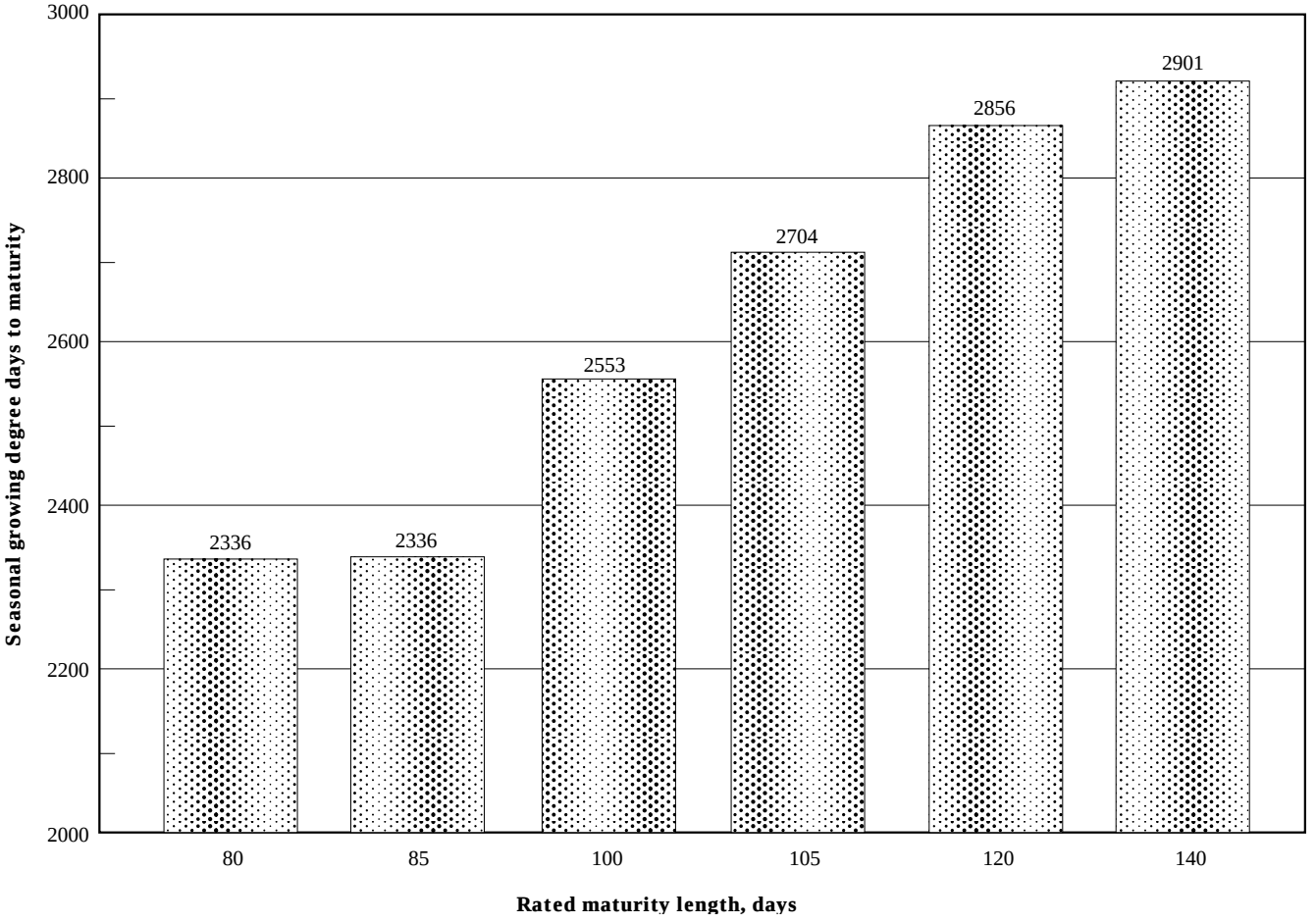
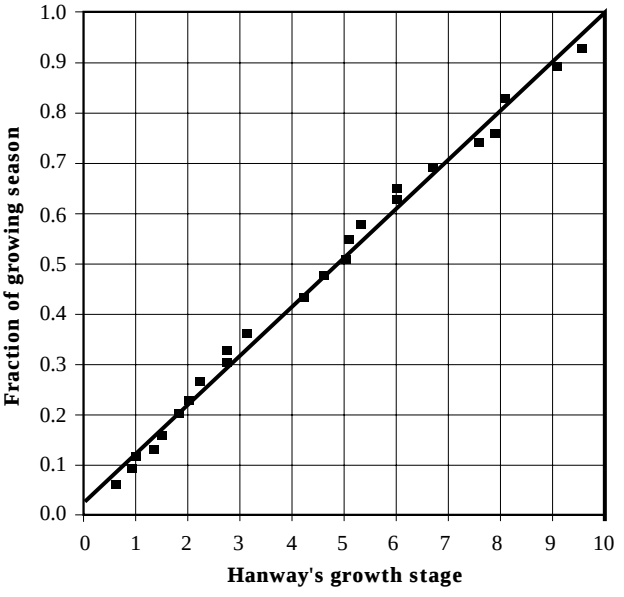


Figure 2–27 Crop growth stages for corn related to the fraction of the growing season based on growing degree days



Example 2–20 Growth adjustment

Given: An average seasonal growth and growing degree relationship as shown in figure 2–24. Suppose the actual year is similar to the year requiring 2,700 GDD to reach maturity as shown in figure 2–25. The observed growth stage in the actual year is stage V8 (i.e., #2) with an associated growing degree accumulation of 630 GDD (see fig. 2–25).

Required:

1. Develop the relationship shown in figure 2–27.
2. Compute the expected number of growing degree days required to reach maturity in the actual year.

Solution:

1. From figure 2–24, S_g = -0.322 + 0.0046 GDD. Compute GDD_m = growing degree days for maturity (when stage of growth = 10) for an average year.

   10 = -0.322 + 0.00446 GDD_m

   Then,

$$GDD_m = \frac{(10 + 0.322)}{0.00446}$$

$$GDD_m = 2,314 \text{ growing degree days}$$

   The relationship for the fraction of growing season is:

$$F_S = \frac{GDD}{GDD_m} \text{ ; or } GDD = F_S\ GDD_m$$

   Substitute part c into a and solve for F_S:

$$S_g = -0.322 + 0.00446(F_S GDD_m)$$

$$F_s = \frac{(S_g + 0.322)}{(0.00446 GDD_m)},$$

$$\text{with } GDD_m = 2,314$$

$$F_s = 0.0969 S_g + 0.031$$

2. Compute F_S for observed stage of growth: F_S = 0.0969 (2) + 0.031 = 0.225

   Use definition of F_S to determine GDD_m:

$$F_S = \frac{GDD}{GDD_m}$$

$$GDD_m = \frac{GDD}{F_S}$$

   Know GDD = 630 GDD for actual year

$$\text{Estimated } GDD_m = \frac{630}{0.225} = 2,800$$

(h) Sensing ground cover

Recently, various devices have been developed to measure the amount of light that penetrates through the canopy and reaches the soil surface. These devices can be used in several ways. They can estimate the current leaf area index (LAI). This is especially useful if a plant canopy has been damaged by wind, hail, or insects. The light measuring devices can also help determine when effective cover has been reached and when maturation begins. If the LAI is more than 3, the crop will have reached effective cover. This can be especially useful if plant populations or row spacings vary considerably. Phene et al. (1985) also used such a device to improve estimates of evaporation from a wet soil surface.

Various sophisticated models (Ritchie 1972 and Hsiao and Henderson 1985) are available to predict crop water use based on leaf area index and percent ground cover. The light bar instruments could allow increased use of these models. However, the models require many other data beyond LAI. Likewise, if crop water use is needed for planning or long-term purposes, the ground cover sensing techniques are not applicable. Thus, although the light measuring devices are a valuable additional tool for managing irrigation, they are not a substitute for the reference crop and crop coefficient approach presented in this publication.

(i) Summary

This section of chapter 2 presented methods to estimate the basal crop coefficients to determine irrigation water requirements, methods to evaluate the effect of water stress and evaporation from wet soil surfaces, and techniques to develop an average crop coefficient for long-term evapotranspiration estimates. Data are provided to approximate water use for many crops. However, local crop coefficient information should be used where available. In all cases local information is needed to predict the length of the growing season and the rate of crop development. The crop coefficients presented in this section are for a clipped grass reference crop. If other reference crop evapotranspiration methods are considered, it is essential that different crop coefficients be used, or the given crop coefficients should be adjusted using the Penman-Monteith method presented in section 623.0203 of this chapter.

623.0205 Leaching requirements for salinity control

(a) Significance of salinity

Most soils and irrigation water contain some soluble salts that are not beneficial for plant growth. Some contain salts that are toxic to plants and animals. Salts originate from dissolution or weathering of rocks or soil and are carried in solution with water. The most common are the saline salts of sodium, chlorine, and boron. Salts accumulate in the irrigated root zone where they are left behind as the soil water is used by the plant in transpiration or through surface evaporation.

Various units are used to describe the amount of salt present in water. The concentration is the mass of salt per unit volume of water. The concentration is expressed as parts of salt per million parts of water (ppm), or as the weight of salts (milligrams) per liter (L) of water (mg/L). The numerical value is the same for either unit (1 ppm = 1 mg/L). Some soil surveys report the concentration as a percentage. One percent is equal to 10,000 ppm. Another unit commonly used to describe the effective concentration is milliequivalents per liter (meq/L). The concentration in meq/L equals the concentration in mg/L divided by the equivalent weight of the respective salt.

Measuring the concentration of salt in soil water is difficult; therefore, simplified methods have been developed to measure and quantify the salinity level. Solutions that contain salt conduct electricity. The electrical conductivity of the soil water (EC_e) is directly proportional to the ionic concentration. The most common unit for EC_e is millimhos per centimeter (mmho/cm). Electrical conductivity is now more commonly expressed as decisiemens per meter (dS/m), where 1 dS/m = 1 mmho/cm. One mmho/cm normally equals a concentration of 640 ppm or 640 mg/L. The standard temperature for measuring the electrical conductivity is 77 °F (25 °C).

The electrical conductivity of the soil water generally is determined by mixing a soil sample with distilled water to a specified consistency called a “saturated paste” from which some water is vacuum extracted. The water that is extracted is called the saturated-soil extract and is used for most chemical analyzes. The electrical conductivity of the saturated-soil extract is denoted as EC_e and is expressed in mmho/cm or dS/m.

If the concentration of soluble salts in the root zone becomes excessive, crop yields are reduced because of physical damage to the plant. The objective of irrigation is to maintain the soil-water content and the salinity level within suitable ranges for optimum plant growth.

Crop yield reductions can result from plant stress caused by the salt concentration (osmotic potential), toxicity of certain specific salts, nutrient imbalances created when specific salts become excessive, or from a reduction of soil permeability. The extent to which salts accumulate in the soil depends upon the irrigation water quantity and quality, irrigation management practices, amount and distribution of rainfall, and the adequacy of drainage.

To prevent yield loss, the salt concentration in the crop root zone must be maintained below a level that affects yield. To prevent soil salinity from reaching these harmful levels, a part of the concentrated salt solution must be leached from the crop root zone. Salts leach whenever the total water application by rainfall or irrigation exceeds depletion by crop evapotranspiration, provided that soil infiltration and drainage rates are adequate. Rainfall, which contains little salt, may remove salts from the root zone. However, in many locations rainfall is inadequate and provisions must be made for adequate leaching through application of additional irrigation water.

Other salinity management alternatives should also be considered. They include more frequent irrigations, other crop selection, seed bed preparation and placement, changing irrigation method, changing water supply, subsurface drainage, nutrient and water management, tillage management, and improving water application distribution uniformity. These alternatives are discussed in greater detail in section 623.0205(e).

Plants extract water from the soil by exerting an absorptive force greater than the attraction of the soil matrix for water. As the soil dries, remaining water in the soil profile is held more tightly to soil particles.

Salts also attract water. The combination of drying soils and elevated salt concentrations result in less water being available for plant uptake. The cumulative effect of salts in a drying clay loam is illustrated in figure 2–28. The reduction in water available to the crop as salinity increases is evident in this figure. Under conditions of low salinity (EC_e = 1 mmho/cm), the available water is about 2 inches per foot. Where the salinity level increases to an average of 16 mmho/cm, the available water is reduced to about 1.6 inches per foot.

Salt affected soils generally are broken into three categories: saline soil, saline-alkali soil, and nonsaline-alkali soil.

Saline soil—This soil contains salts that provide an electrical conductivity of the soil-water extract, EC_e of more than 4.0 mmho/cm, and an exchangeable sodium percentage (ESP) of less than 15. The principal anions are chloride, sulfate, small amounts of bicarbonate, and occasionally some nitrate.

Saline-sodic soil—This soil contains salts that provide an EC_e of more than 4.0 mmho/cm and an ESP of more than 15. It is difficult to leach because the clay colloids are dispersed.

Nonsaline-sodic soil—This soil contains salts that provide an EC_e of less than 4.0 mmho/cm and an ESP of more than 15. It is commonly called "black alkali" or "slick spots."

(b) Water quality evaluation

The water's suitability for irrigation depends on the total amount and kind of salts in the water, the crops grown, soil properties, irrigation management, cultural practices, and climatic factors. The relative amount of various cations in the saturated-soil extract is used to characterize the soil water. Sodium Absorption Ratio (SAR), the most often used term, is defined as:

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}} \qquad [2–69]$$

where:
Na, Ca, and Mg = concentrations of sodium, calcium, and magnesium (meq/L)

The adjusted SAR procedure presented in the first edition of the Food and Agriculture Organization's FAO-29 is no longer recommended (Ayres & Westcot 1985).

The evaluation of water quality is based on the kind of problems most commonly encountered with salt-affected water—salinity, permeability, and toxicity—and other miscellaneous effects. S**alinity** describes the conditions where salts in the root zone reduce soil-water availability (as illustrated in fig. 2–28) to such an extent that yield is affected.

A **permeability** problem occurs when the soil or water is relatively high in sodium, or low in calcium, so that the infiltration rate decreases to the point that sufficient water cannot infiltrate to adequately supply the crop. Where exchangeable sodium is excessive, soil permeability is reduced for a given salinity level of the infiltrating water and soil pH. Low salinity and high pH can also decrease soil permeability as much as sodium.

The exact level of sodium that causes problems is difficult to quantify because it depends on at least the soil texture, mineralogy, organic matter, and soil and water management. Certain ions (sodium, boron, or chloride) from soil or water may accumulate in concentrations high enough to reduce yields in sensitive crops. This reaction is described as specific ion **toxicity**.

Figure 2–28 Example soil-water retention curves for a clay-loam soil at various degrees of soil salinity (EC_e) (Ayers and Westcot 1985)

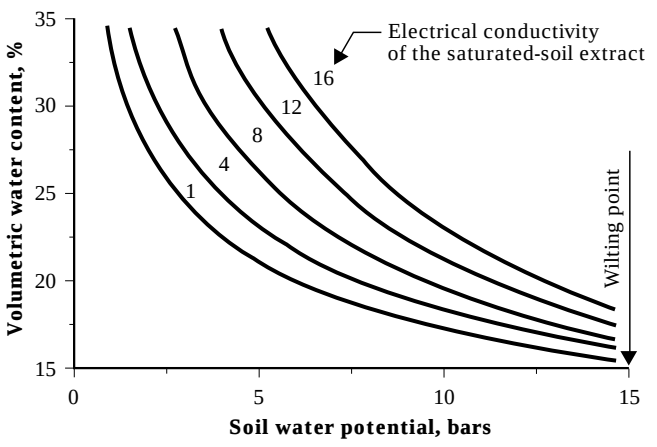


Table 2–32 Irrigation water quality guidelines [1/]

Potential irrigation water quality problem	Describing parameter	- - - - - Degree of restriction on use - - - - - None	Slight to moderate	Severe
Salinity				
(affects crop water availability)	EC_i [2/], mmho/cm	< 0.7	0.7 – 3.0	> 3.0
	or TDS [3/], mg/L	< 450	450 – 2,000	> 2,000
Infiltration				
(affects water infiltration rate— evaluated by using EC_i and SAR together) [4/]	SAR		EC_i, mmho/cm	
	0 – 3	> 0.7	0.7 – 0.2	< 0.2
	3 – 6	> 1.2	1.2 – 0.3	< 0.3
	6 – 12	> 1.9	1.9 – 0.5	< 0.5
	12 – 20	> 2.9	2.9 – 1.3	< 1.3
	20 – 40	> 5.0	5.0 – 2.9	< 2.9
Specific ion toxicity				
(affects sensitive crops)				
Sodium (Na) [5/]				
surface irrigation	SAR	< 3	3 – 9	> 9
sprinkler irrigation	meq/L	< 3	> 3	
Chloride (Cl) [5/]				
surface irrigation	meq/L	< 4	4 – 10	> 10
sprinkler irrigation	meq/L	< 3	> 3	
Boron (B) [6/]	meq/L	< 0.7	0.7 – 3.0	> 3.0
Miscellaneous effects				
(affects susceptible crops)				
Bicarbonate (HCO_3)				
(overhead sprinkling only)	meq/L	< 1.5	1.5 – 8.5	> 8.5

1/ Adapted from Ayers and Westcot (1985), FAO 29, revision 1.

2/ EC_i means electrical conductivity of the irrigation water reported in mmho/cm at 77 °F (25 °C).

3/ TDS means total dissolved solids reported in mg/L.

4/ SAR means sodium adsorption ratio. At a given SAR, infiltration rate increases as water salinity increases.

5/ For surface irrigation—Most tree crops and woody plants are sensitive to sodium and chloride, so the values shown should be used. Because most annual crops are not sensitive, the salinity tolerance values in table 2–34 should be used. For chloride tolerance of selected fruit crops, see table 2–35. With overhead sprinkler irrigation and low humidity (<30%), sodium and chloride may be absorbed through the leaves of sensitive crops. For crop sensitivity to absorption, see table 2–36.

6/ For boron tolerances see tables 2–37 and 2–38.

Guidelines for evaluating water quality for irrigation are given in table 2–32. These guidelines are limited to water quality parameters that are normally encountered and that materially affect crop production. They are meant as an initial management guide and involve several assumptions. Specific discussion regarding the information this table is in Ayers and Westcot (1985). The division of this table into "Restriction on Use" is somewhat arbitrary because changes are gradual. Changes of 10 to 20 percent above or below the guideline values have little significance if considered in perspective with other factors affecting yield.

Distinction must be made between the electrical conductivity of the irrigation water (EC_i) and the applied water (EC_{aw}), including rainfall, and the saturated-soil extract (EC_e). The soil salinity expressed as EC_e depends upon the electrical conductivity of the irrigation water and the amount of leaching that is taking place. These relationships are discussed in a later section where the leaching requirement is defined. Figures 2–29 and 2–30 may also be used to assess the salinity hazard as a function of irrigation water quality (Rhoades and Loveday 1990). Likewise, figure 2–31 can be used to determine the likelihood of a permeability hazard.

Laboratory determinations and calculations needed to use the guidelines of table 2–32 are in table 2–33. Analytical procedures for the laboratory determinations are given in several publications including USDA Agricultural Handbook 60 (USDA 1954) and others.

Table 2–33 Determinations normally required to evaluate irrigation water quality problems [1/]

Determination		Symbol	Valence	Unit of measure [2/]	Atomic weight	Usual range in irrigation water
Total salt content						
Electrical conductivity		EC	—	mmho/cm	—	0-3
Concentration or total dissolved solids		TDS	—	mg/L	—	0-2000
Sodium hazard						
Sodium adsorption ratio [3/]		SAR	—	—	—	0-15
Constituents						
Cations:	Calcium	Ca	+2	meq/L	40.1	0-20
	Magnesium	Mg	+2	meq/L	24.3	0-5
	Sodium	Na	+1	meq/L	23.0	0-40
Anions:	Bicarbonate	HCO_3	-1	meq/L	61.0	0-10
	Sulfate	SO_4	-2	meq/L	96.1	0-20
	Chloride	Cl	-1	meq/L	35.3	0-30
Trace elements						
Boron		B	—	mg/L	10.8	0-2
Acid/basic		pH	—	1-14	—	6.0-8.5

1/ Adapted from Ayers and Westcot (1985).

2/ Millimhos/cm (1 mmho/cm) referenced to 77 °F (25 °C).
mg/L = milligram per liter ≈ parts per million (ppm).
meq/L = milliequivalent per liter (mg/L ÷ equivalent weight = meq/L).

3/ SAR is calculated by the following equation, with each concentration reported in meq/L.

$$SAR = \frac{Na}{\sqrt{\frac{(Ca+Mg)}{2}}}$$

Figure 2–29 Relationship among average root zone salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of **conventional irrigation** management (adapted from Rhoades 1982)

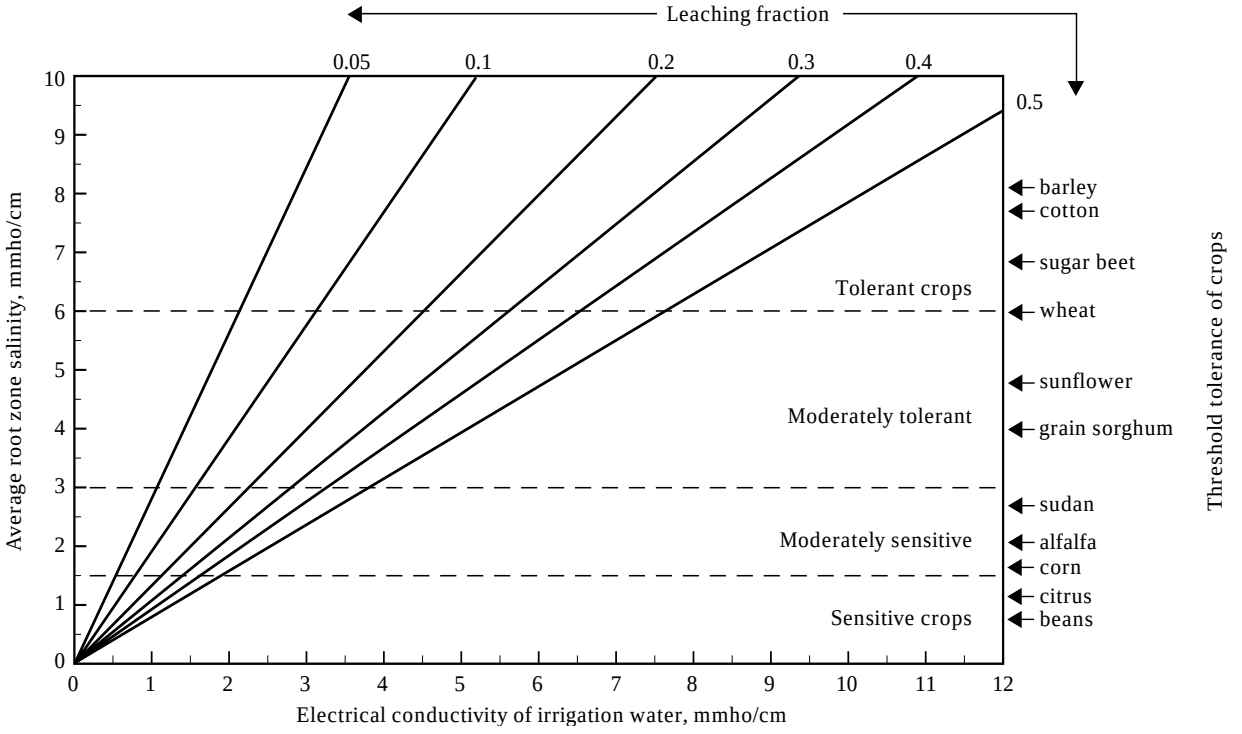


Figure 2–30 Relationship among water uptake-weighted salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of **high-frequency irrigation** (adapted from Rhoades 1982)

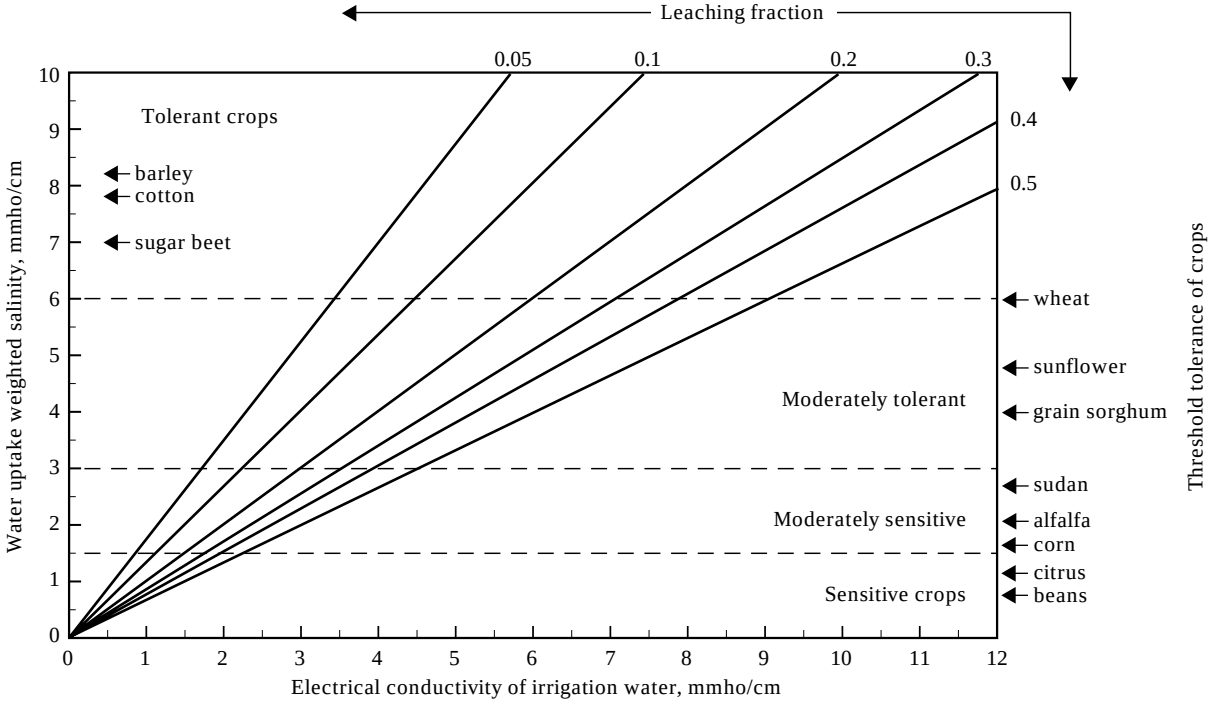
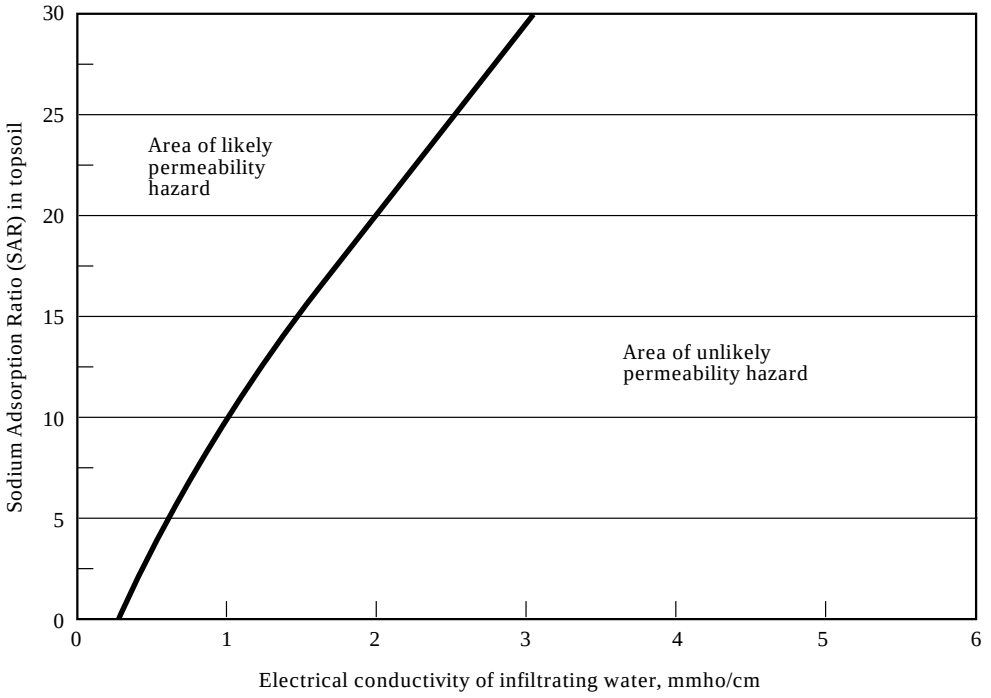


Figure 2–31 Threshold values of Sodium Adsorption Ratio of topsoil and electrical conductivity of infiltrating water associated with the likelihood of substantial losses in permeability (adapted from Rhoades 1982)



(c) Crop salt tolerance

(1) Plant response to salts

Increasing salinity levels in the crop root zone incrementally suppresses growth and crop yield until the plant dies. Suppression typically depends more on osmotic stress created by the total concentration of soluble salts than on specific ion effects.

Although salinity affects plants in many ways, visible symptoms, such as leaf burn or necrosis, seldom occur. Crop yields will have been reduced drastically when symptoms do become visible. Salinity can cause morphological and anatomical changes, which in some cases may improve plant survival, but with reduced yields. Adaptations, which vary with plant species and the type of salinity, include fewer and smaller leaves and thickening of leaf cuticles.

The sensitivity of plants to salt varies with growth stage. Salt tolerance at emergence is normally based on survival rates, whereas tolerance after emergence is based on decreases in plant growth or yield. Crops generally are as salt tolerant at germination as at later stages of development. During germination the salt concentrations are usually higher in the limited root zone because of soil evaporation and plant transpiration from the soil surface layer. Such crops as barley, corn, rice, sorghum and wheat are most sensitive during seedling and early reproductive growth and are more tolerant during later growth stages (Maas 1990).

Many environmental factors interact with salinity to influence crop salt tolerance. Most crops are more sensitive to salinity under hot, dry conditions than cool, humid ones. High atmospheric humidity with no wind alone tends to increase the salt tolerance of some crops, generally benefitting salt-sensitive crops more than salt-tolerant ones.

Soil fertility may also alter plant response under saline conditions. Crops grown on infertile soils may seem more salt tolerant than those grown with adequate fertility because fertility, not salinity, is the growth-limiting factor. Proper fertilization would increase yields whether or not the soil was saline, but proportionately more if it was not saline. Application of fertilizers, including nitrogen, phosphorus, and potassium, above normally adequate levels under saline conditions is a questionable practice. Excess applications of nitrogen have been reported to increase salt tolerance in some crops; others have reported decreases. Phosphorous levels in soil, even with heavy applications, are rarely excessive because phosphorous is adsorbed or precipitated in the soil. Excessive potassium rates do not appear to influence salt tolerance.

(2) Salt tolerance evaluation

The ability of plants to produce economic yields in a saline environment is termed salt tolerance. Agricultural crops differ significantly in their response to excessive concentrations of soluble salts in the root zone. Thus, crop selection is one of the primary options available to growers to maximize productivity under saline conditions. The effects of salinity on crop production are typically divided into two categories:

- **Salt tolerance**—the adverse effect on crop yields of dissolved salts in the soil solution that increases osmotic stress.
- **Toxicity—**caused by specific solutes that reduce growth and yield beyond that attributable to osmotic effects.

The relative salt tolerances of selected agricultural crops are summarized in table 2–34. The table lists two essential parameters sufficient to evaluate salt tolerance: (1) the threshold salinity level, which is the maximum allowable salinity that does not reduce yield measurably below that of a nonsaline condition, and (2) the yield decrease per unit of salinity increase beyond the threshold. All salinity levels are reported as EC_e (the electrical conductivity of the saturated-soil extract reported in mmho/cm and corrected for temperature to 77 °F). A qualitative salt-tolerance rating is also given for relative comparisons among crops. These ratings are defined by the boundaries shown in figure 2–32.

In equation form, the salt tolerance is represented by:

[2–70]

$$\begin{aligned} Y_r &= 100 && 0 \le EC_e \le EC_t \\ &= 100 - Y_d\left(EC_e - EC_t\right) && EC_t \le EC_e \le EC_y \\ &= 0 && EC_e > EC_y \end{aligned}$$

where:

Y_r = the relative crop yield (actual yield at the given salinity level divided by yield with no salinity effect)

EC_e = the average root zone salinity (mmho/cm)

EC_t = the threshold salinity level (mmho/cm)

Y_d = the yield decrease per unit of salinity increase (% per mmho/cm)

EC_y = the level of soil salinity above which the yield is zero

For example, alfalfa (table 2–34) yields decrease about 7.3 percent per unit of salinity increase when the soil salinity exceeds 2.0 mmho/cm (EC_t = 2 mmho/cm, Y_d=7.3%). Therefore, at a soil salinity of 5.4 mmho/cm (EC_e = 5.4 mmho/cm), the relative yield for alfalfa is:

$$Y_r = 100 - 7.3\ (5.4 - 2.0) = 75\%$$

The data presented in table 2–34 were developed from experiments where the salinity treatments were imposed after the seedling stage. Therefore, they do not necessarily represent salt tolerance for the germination and early seedling growth stages.

The threshold and slope coefficients given in this table were typically established from small field plot experiments where large quantities of water were applied to minimize differences in soil salinity through the crop root zone. The question frequently arises as to the applicability of the coefficients to field conditions. Hoffman (1986) reported that several unrelated tests have provided evidence that the coefficients are valid over a range of leaching fractions, irrigation intervals, and soil salinity profiles.

Figure 2–32 Divisions for classifying crop tolerance to salinity (adapted from Maas 1986)

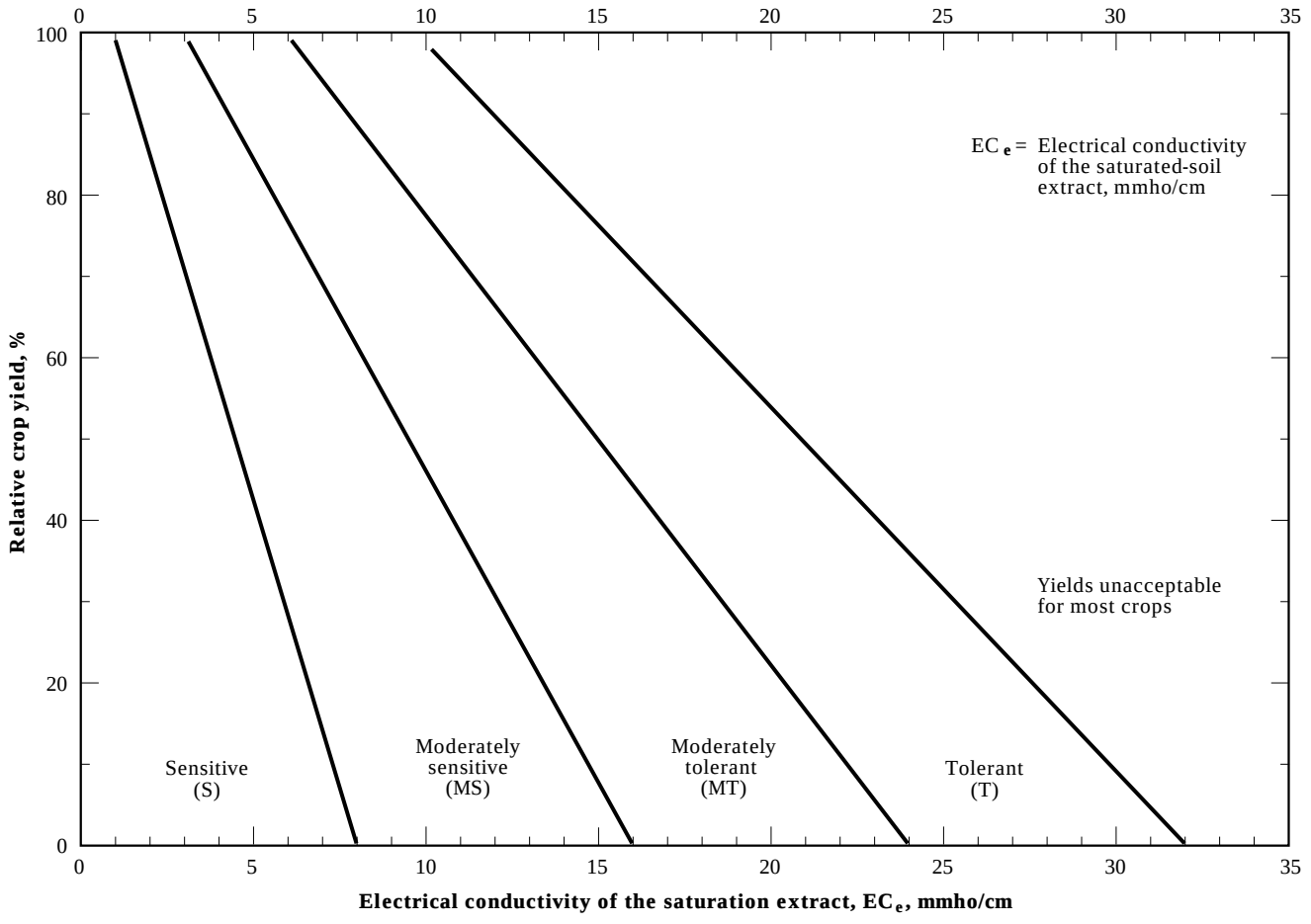


Table 2–34 Salt tolerance of selected crops [1]

Common name	Botanical name	Salt tolerance threshold [2] (EC_t)	Yield decline [3] (Y_d)	Qualitative salt tolerance rating [4]
		mmho/cm	% per mmho/cm	
Field crops				
Barley	*Hordeum vulgare*	8.0	5.0	T
Bean	*Phaseolus vulgaris*	1.0	19	S
Broad bean	*Vicia faba*	1.6	9.6	MS
Corn	*Zea Mays*	1.7	12	MS
Cotton	*Gossypium hirsutum*	7.7	5.2	T
Cowpea	*Vigna unguiculata*	4.9	12	MT
Flax	*Linum usitatissimum*	1.7	12	MS
Guar	*Cyamopsis tetragonoloba*	8.8	17.0	T
Millet, foxtail	*Setaria italica*	—	—	MS
Oats	*Avena sativa*	—	—	MT
Peanut	*Arachis hypogaea*	3.2	29	MS
Rice, paddy [5]	*Oryza sativa*	3.0	12	S
Rye	*Secale cereale*	11.4	10.8	T
Safflower	*Carthamus tinctorius*	—	—	MT
Sesame	*Sesamum indicum*	—	—	S
Sorghum	*Sorghum bicolor*	6.8	16	MT
Soybean	*Glycine max*	5.0	20	MT
Sugar beet	*Beta vulgaris*	7.0	5.9	T
Sugarcane	*Saccharum officinarum*	1.7	5.9	MS
Sunflower	*Helianthus annuus*	—	—	MS
Triticale	*x Triticosecale*	6.1	2.5	T
Wheat	*Triticum aestivum*	6.0	7.1	MT
Wheat (semidwarf)	*T. aestivum*	8.6	3.0	T
Wheat, durum	*T. turgidum*	5.9	3.8	T
Grasses and forage crops				
Alfalfa	*Medicago sativa*	2.0	7.3	MS
Alkaligrass, nuttall	*Puccinellia airoides*	—	—	T
Alkali sacaton	*Sporobolus airoides*	—	—	T
Barley (forage)	*Hordeum vulgare*	6.0	7.1	MT
Bentgrass	*Agrostis stolonifera palustris*	—	—	MS
Bermudagrass	*Cynodon dactylon*	6.9	6.4	T
Bluestem, angleton	*Dichanthium aristatum*	—	—	MS
Brome, mountain	*Bromus marginatus*	—	—	MT
Brome, smooth	*B. inermis*	—	—	MS
Buffelgrass	*Cenchrus ciliaris*	—	—	MS
Burnet	*Poterium sanguisorba*	—	—	MS
Canarygrass, reed	*Phalaris arundinacea*	—	—	MT

See footnotes at end of table.

Table 2–34 Salt tolerance of selected crops[1/]—Continued

Common name	Botanical name	Salt tolerance threshold [2/] (EC_t)	Yield decline [3/] (Y_d)	Qualitative salt tolerance rating [4/]
		mmho/cm	% per mmho/cm	
Grasses and forage crops (continued)				
Clover, alsike	*Trifolium hybridum*	1.5	12	MS
Clover, berseem	*T. alexandrinum*	1.5	5.7	MS
Clover, hubam	*Melilotus alba*	—	—	MT
Clover, ladino	*Trifolium repens*	1.5	12	MS
Clover, red	*T. pratense*	1.5	12	MS
Clover, strawberry	*T. fragiferum*	1.5	12	MS
Clover, sweet	*Melilotus*	—	—	MT
Clover, white Dutch	*Trifolium repens*	—	—	MS
Corn (forage)	*Zea mays*	1.8	7.4	MS
Cowpea (forage)	*Vigna unguiculata*	2.5	11	MS
Dallisgrass	*Paspalum dilatatum*	—	—	MS
Fescue, tall	*Festuca elatior*	3.9	5.3	MT
Fescue, meadow	*F. pratensis*	—	—	MT
Foxtail, meadow	*Alopecurus pratensis*	1.5	9.6	MS
Grama, blue	*Bouteloua gracilis*	—	—	MS
Hardinggrass	*Phalaris tuberosa*	4.6	7.6	MT
Kallar grass	*Diplachne fusca*	—	—	T
Lovegrass	*Eragrostis sp.*	2.0	8.4	MS
Milkvetch, cicer	*Astragalus cicer*	—	—	MS
Oatgrass, tall	*Arrhenatherum, Danthonia*	—	—	MS
Oats (forage)	*Avena sativa*	—	—	MS
Orchardgrass	*Dactylis glomerata*	1.5	6.2	MS
Panicgrass, blue	*Panicum antidotale*	—	—	MT
Rape	*Brassica napus*	—	—	MT
Rescuegrass	*Bromus unioloides*	—	—	MT
Rhodesgrass	*Chloris gayana*	—	—	MT
Rye (forage)	*Secale cereale*	—	—	MS
Ryegrass, Italian	*Lolium italicum multiflorum*	—	—	MT
Ryegrass, perennial	*L. perenne*	5.6	7.6	MT
Saltgrass, desert	*Distichlis stricta*	—	—	T
Sesbania	*Sesbania exaltata*	2.3	7.0	MS
Siratro	*Macroptilium atropurpureum*	—	—	MS
Sphaerophysa	*Sphaerophysa salsula*	2.2	7.0	MS
Sudangrass	*Sorghum sudanense*	2.8	4.3	MT
Timothy	*Phleum pratense*	—	—	MS
Trefoil, big	*Lotus uliginosus*	2.3	19	MS
Trefoil, narrowleaf birdsfoot	*L. corniculatus tenuifolium*	5.0	10	MT
Trefoil, broadleaf birdsfoot	*L. corniculatus arvenis*	—	—	MT

See footnotes at end of table.

Table 2–34 Salt tolerance of selected crops[1/]—Continued

Common name	Botanical name	Salt tolerance threshold [2/] (EC_t)	Yield decline [3/] (Y_d)	Qualitative salt tolerance rating [4/]
		mmho/cm	% per mmho/cm	
Grasses and forage crops (continued)				
Vetch, common	*Vicia angustifolia*	3.0	11	MS
Wheat (forage)	*Triticum aestivum*	4.5	2.6	MT
Wheat, durum (forage)	*T. turgidum*	2.1	2.5	MT
Wheatgrass, standard crested	*Agropyron sibiricum*	3.5	4.0	MT
Wheatgrass, fairway crested	*A. cristatum*	7.5	6.9	T
Wheatgrass, intermediate	*A. intermedium*	—	—	MT
Wheatgrass, slender	*A. trachycaulum*	—	—	MT
Wheatgrass, tall	*A. elongatum*	7.5	4.2	T
Wheatgrass, western	*A. smithii*	—	—	MT
Wildrye, Altai	*Elymus angustus*	—	—	T
Wildrye, beardless	*E. triticoides*	2.7	6.0	MT
Wildrye, Canadian	*E. canadensis*	—	—	MT
Wildrye, Russian	*E. junceus*	—	—	T
Vegetable and fruit crops				
Artichoke	*Helianthus tuberosus*	—	—	MT
Asparagus	*Asparagus officinalis*	4.1	2.0	T
Bean	*Phaseolus vulgaris*	1.0	19	S
Beet, red	*Beta vulgaris*	4.0	9.0	MT
Broccoli	*Brassica oleracea botrytis*	2.8	9.2	MS
Brussels sprouts	*B. oleracea gemmifera*	—	—	MS
Cabbage	*B. oleracea capitata*	1.8	9.7	MS
Carrot	*Daucus carota*	1.0	14	S
Cauliflower	*B. oleracea botrytis*	—	—	MS
Celery	*Apium graveolens*	1.8	6.2	MS
Corn, sweet	*Zea mays*	1.7	12	MS
Cucumber	*Cucumis sativus*	2.5	13	MS
Eggplant	*Solanum melongena esculentum*	1.16.9	MS	
Kale	*B. oleracea acephala*	—	—	MS
Kohlrabi	*B. oleracea gongylodes*	—	—	MS
Lettuce	*Lactuca sativa*	1.3	13	MS
Muskmelon	*Cucumis melo*	—	—	MS
Okra	*Abelmoschus esculentus*	—	—	S
Onion	*Allium cepa*	1.2	16	S
Parsnip	*Pastinaca sativa*	—	—	S
Pea	*Pisum sativum*	—	—	S
Pepper	*Capsicum annuum*	1.5	14	MS
Potato	*Solanum tuberosum*	1.7	12	MS

See footnotes at end of table.

Table 2–34 Salt tolerance of selected crops[1/]—Continued

Common name	Botanical name	Salt tolerance threshold [2/] (EC_t)	Yield decline [3/] (Y_d)	Qualitative salt tolerance rating [4/]
		mmho/cm	% per mmho/cm	
Vegetable and fruit crops (continued)				
Pumpkin	*Cucurbita pepo pepo*	—	—	MS
Radish	*Raphanus sativus*	1.2	13	MS
Spinach	*Spinacia oleracea*	2.0	7.6	MS
Squash, scallop	*Cucurbita pepo melopepo*	3.2	16	MS
Squash, zucchini	*C. pepo melopepo*	4.7	9.4	MT
Strawberry	*Fragaria sp.*	1.0	33	S
Sweet potato	*Ipomoea batatas*	1.5	11	MS
Tomato	*Lycopersicon lycopersicum*	2.5	9.9	MS
Turnip	*Brassica rapa*	0.9	9.0	MS
Watermelon	*Citrullus lanatus*	—	—	MS
Woody crops				
Almond	*Prunus dulcis*	1.5	19	S
Apple	*Malus sylvestris*	—	—	S
Apricot	*P. armeniaca*	1.6	24	S
Avocado	*Persea americana*	—	—	S
Blackberry	*Rubus sp.*	1.5	22	S
Boysenberry	*Rubus ursinus*	1.5	22	S
Castor bean	*Ricinus communis*	—	—	MS
Cherimoya	*Annona cherimola*	—	—	S
Cherry, sweet	*Prunus avium*	—	—	S
Cherry, sand	*P. besseyi*	—	—	S
Currant	*Ribes sp.*	—	—	S
Date palm	*Phoenix dactylifera*	4.0	3.6	T
Fig	*Ficus carica*	—	—	MT
Gooseberry	*Ribes sp.*	—	—	S
Grape	*Vitis sp.*	1.5	9.6	MS
Grapefruit	*Citrus paradisi*	1.8	16	S
Guayule	*Parthenium argentatum*	8.7	11.6	T
Jojoba	*Simmondsia chinensis*	—	—	T
Jujube	*Ziziphus jujuba*	—	—	MT
Lemon	*C. limon*	—	—	S
Lime	*C aurantiifolia*	—	—	S
Loquat	*Eriobotrya japonica*	—	—	S
Mango	*Mangifera indica*	—	—	S
Olive	*Olea europaea*	—	—	MT
Orange	*C. sinensis*	1.7	16	S
Papaya	*Carica papaya*	—	—	MT

See footnotes at end of table.

Table 2–34 Salt tolerance of selected crops[1/]—Continued

Common name	Botanical name	Salt tolerance threshold [2/] (EC_t)	Yield decline [3/] (Y_d)	Qualitative salt tolerance rating [4/]
		mmho/cm	% per mmho/cm	
Woody crops (continued)				
Passion fruit	*Passiflora edulis*	—	—	S
Peach	*Prunus persica*	1.7	21	S
Pear	*Pyrus communis*	—	—	S
Persimmon	*Diospyros virginiana*	—	—	S
Pineapple	*Ananas comosus*	—	—	MT
Plum; prune	*Prunus domestica*	1.5	18	S
Pomegranate	*Punica granatum*	—	—	MT
Pummelo	*Citrus maxima*	—	—	S
Raspberry	*Rubus idaeus*	—	—	S
Rose apple	*Syzygium jambos*	—	—	S
Sapote, white	*Casimiroa edulis*	—	—	S
Tangerine	*Citrus reticulata*	—	—	S

1/ Adapted from Maas and Hoffman (1977) and Maas (1990). Data serve as a guide to relative tolerances. Absolute tolerances depend upon climate, soil conditions, and cultural practices. Note: 1 mmho/cm = 1 dS/m.

2/ Salt tolerance threshold (EC_t) is the mean soil salinity at initial yield decline. Salinity expressed as EC_e in mmho/cm referenced to 77 °F (25 °C).

3/ Percent yield decline (Y_d) is the rate of yield reduction per unit increase in salinity beyond the threshold.

4/ Qualitative salt tolerance ratings are sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T) as shown in figure 2–32.

5/ Values are for soil water while plants are submerged. Less tolerant during seedling stage.

(3) Specific ion effects

Toxicity problems are different from those of salinity because they occur within the plant and are not caused by osmotic potential or water stress. Toxicity normally results when certain ions are absorbed with soil-water, move with the plant transpiration stream, and accumulate in the leaves at concentrations that cause plant damage. The extent of damage depends upon the specific ion concentration, crop sensitivity, crop growth stage, and crop water use rate and time. The usual toxic ions present in irrigation water include chloride, sodium, and boron. Not all crops are sensitive to these ions. Most annual crops are not sensitive at the concentrations given in table 2–32. However, many tree crops and other woody perennials are susceptible. Toxicity often accompanies or complicates a salinity or infiltration problem although it may appear even when salinity is low.

Chemical analysis of plant tissue, soil-water extract, or irrigation water is most commonly used to identify toxicity problems. Leaf injury symptoms appear in chloride-sensitive crops when leaves accumulate about 0.3 to 0.5 percent chloride on a dry weight basis. Maximum permissible concentrations of chloride in the saturated-soil extract for several crops are given in table 2–35.

Symptoms of sodium toxicity occur first on older leaves as a burning or drying of tissue at the outer edges of the leaf. As severity increases, the affected zone progresses toward the center of the leaf between the veins. Sodium toxicity is often modified and reduced if calcium is present. Because of this interaction, a reasonable evaluation of the potential toxicity is given by the exchangeable-sodium-percentage (ESP) of the soil or the SAR of saturated-soil extracts or irrigation water (USDA 1954). Tolerances of representative crops to sodium are given in table 2–36.

Boron is an essential minor element, but if concentrations exceed only slightly that required for optimum plant growth, it becomes toxic. Boron toxicity symptoms typically appear at the tip and along the edges of older leaves as yellowing, spotting, drying of leaf tissue, or a combination of these. The damage gradually progresses toward midleaf. A wide range of crops has been tested for boron tolerance in sand cultures. The results of these tests are summarized in tables 2–37 and 2–38. These data were based on the boron level at which toxicity symptoms were observed, and do not necessarily indicate corresponding yield reductions.

Table 2–35 Chloride tolerance limits of some fruit crop cultivars and rootstocks [1/]

Crop	Rootstock or cultivar	Maximum permissible chloride concentration of saturated-soil extract without leaf injury [2/] (meq/L)
	Rootstocks	
Avocado	West Indian	7.5
(Persea americana)	Guatemalan	6.0
	Mexican	5.0
Citrus	Sunki Mandarin	25.0
(Citrus spp.)	grapefruit	25.0
	Cleopatra mandarin	25.0
	Rangpur lime	25.0
	Sampson tangelo	15.0
	rough lemon	15.0
	sour orange	15.0
	Ponkan mandarin	15.0
	Citrumelo 4475	10.0
	trifoliate orange	10.0
	Cuban shaddock	10.0
	Calamondin	10.0
	sweet orange	10.0
	Savage citrange	10.0
	Rusk citrange	10.0
	Troyer citrange	10.0
Grape	Salt Creek, 1613-3	40.0
(Vitis spp.)	Dog Ridge	30.0
Stone Fruits	Marianna	25.0
(Prunus spp.)	Lovell, Shalil	10.0
	Yunnan	7.5
	Cultivars	
Berries	Boysenberry	10.0
(Rubus spp.)	Olallie blackberry	10.0
	Indian summer raspberry	5.0
Grape	Thompson seedless	20.0
(Vitis spp.)	Perlette	20.0
	Cardinal	10.0
	Black Rose	10.0
Strawberry	Lassen	7.5
(Fragaria spp.)	Shasta	5.0

1/ Adapted from Maas (1990).
2/ For some crops, the concentration given may exceed the overall salinity tolerance of that crop and cause some yield reduction.

Table 2–36 Relative tolerance of selected crops to foliar injury from saline water applied by sprinklers [1/2/]

Na^+ or Cl^- concentrations causing foliar injury [3/]			
< 5 meq/L	**5 – 10 meq/L**	**10 – 20 meq/L**	**> 20 meq/L**
Almond *(Prunus dulcis)*	Grape *(Vitis spp.)*	Alfalfa (Medicago sativa)	Cauliflower *(Brassica oleracea botrytis)*
Apricot *(Prunus armeniaca)*	Pepper *(Capsicum annuum)*	Barley (Hordeum vulgare)	Cotton *(Gossypium hirsutum)*
Citrus *(Citrus spp.)*	Potato *(Solanum tuberosum)*	Maize (corn) (Zea mays)	Sugar beet *(Beta vulgaris)*
Plum *(Prunus domestica)*	Tomato *(Lycopersicon lycopersicum)*	Cucumber (Cucumis sativus)	Sunflower *(Helianthus annuus)*
		Safflower (Carthamus tinctorius)	
		Sesame (Sesamum indicum)	
		Sorghum (Sorghum bicolor)	

1/ Data taken from Maas (1990).

2/ Susceptibility based on direct accumulation of salts through the leaves.

3/ Leaf absorption and foliar injury are influenced by cultural and environmental conditions, such as drying winds, low humidity, speed of rotation of sprinklers, and the timing and frequency of irrigations. Data presented are only general guidelines for late spring and summer daytime sprinkling.

Table 2–37 Boron tolerance limits for agricultural crops [1/ 2/]

Common plant name	Scientific plant name
Very sensitive (<0.5 mg/L)	
Blackberry [3/]	*Rubus spp.*
Lemon [3/]	*Citrus limon*
Sensitive (0.5 – 0.75 mg/L)	
Apricot [3/]	*Prunus armeniaca*
Avocado [3/]	*Persea americana*
Cherry [3/]	*Prunus avium*
Fig, kadota [3/]	*Ficus carica*
Grape [3/]	*Vitis vinifera*
Grapefruit [3/]	*Citrus X paradisi*
Onion	*Allium cepa*
Orange [3/]	*Citrus sinensis*
Peach [3/]	*Prunus persica*
Pecan [3/]	*Carya illinoiensis*
Persimmon [3/]	*Diospyros kaki*
Plum [3/]	*Prunus domestica*
Walnut [3/]	*Juglans regia*
Sensitive (0.75 – 1.0 mg/L)	
Artichoke, Jerusalem [3/]	*Helianthus tuberosus*
Bean, kidney [3/]	*Phaseolus vulgaris*
Bean, lima [3/]	*Phaseolus lunatus*
Bean, mung [3/]	*Vigna radiata*
Garlic	*Allium sativum*
Groundnut/Peanut	*Arachis hypogaea*
Lupine [3/]	*Lupinus hartwegii*
Sesame [3/]	*Sesamum indicum*
Strawberry [3/]	*Fragaria spp.*
Sunflower	*Helianthus annuus*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Moderately sensitive (1 – 2 mg/L)	
Broccoli	*Brassica oleracea botrytis*
Carrot	*Daucus carota*
Cucumber	*Cucumis sativus*
Lettuce [3/]	*Lactuca sativa*
Pea [3/]	*Pisum sativa*
Pepper, red	*Capsicum annuum*
Potato	*Solanum tuberosum*
Radish	*Raphanus sativus*
Moderately tolerant (2.0 – 4.0 mg/L)	
Artichoke [3/]	*Cynara scolymus*
Barley	*Hordeum vulgare*
Bluegrass, Kentucky [3/]	*Poa pratensis*
Cabbage [3/]	*Brassica oleracea capitata*
Cauliflower	*Brassica oleracea botrytis*
Clover, sweet [3/]	*Melilotus indica*
Cowpea [3/]	*Vigna unguiculata*
Maize (corn)	*Zea mays*
Muskmelon [3/]	*Cucumis melo*
Mustard [3/]	*Brassica juncea*
Squash	*Cucurbita pepo*
Tobacco [3/]	*Nicotiana tabacum*
Turnip	*Brassica rapa*
Tolerant (4.0-6.0 mg/L)	
Alfalfa [3/]	*Medicago sativa*
Beet, red	*Beta vulgaris*
Parsley [3/]	*Petroselinum crispum*
Sugarbeet	*Beta vulgaris*
Tomato	*Lycopersicon lycopersicum*
Vetch, purple [3/]	*Vicia benghalensis*
Very Tolerant (6.0-15.0 mg/L)	
Asparagus	*Asparagus officinalis*
Celery [3/]	*Apium graveolens*
Cotton	*Gossypium hirsutum*
Sorghum	*Sorghum bicolor*

1/ Data taken from Maas (1990).

2/ Maximum concentrations tolerated in soil-water without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions, and crop varieties.

3/ Tolerance based on reductions in vegetative growth.

Table 2–38 Citrus and stone fruit rootstocks ranked in order of increasing boron accumulation and transport to leaves[1/]

Common name	Botanical name	Level of boron accumulation
Citrus		Low
Alemow	*Citrus macrophylla*	|
Gajanimma	*Citrus pennivesiculata or Citrus moi*	|
Chinese box orange	*Severinia buxifolia*	|
Sour orange	*Citrus aurantium*	|
Calamondin	*X Citrofortunella mitis*	|
Sweet orange	*Citrus sinensis*	|
Yuzu	*Citrus junos*	|
Rough lemon	*Citrus limon*	|
Grapefruit	*Citrus X paradisi*	|
Rangpur lime	*Citrus X limonia*	|
Troyer citrange	*X Citroncirus webberi*	|
Savage citrange	*X Citroncirus webberi*	|
Cleopatra mandarin	*Citrus reticulata*	|
Rusk citrange	*X Citroncirus webberi*	|
Sunki mandarin	*Citrus reticulata*	|
Sweet lemon	*Citrus limon*	|
Trifoliate orange	*Poncirus trifoliata*	|
Citrumelo 4475	*Poncirus trifoliata X Citrus paradisi*	|
Ponkan mandarin	*Citrus reticulata*	|
Sampson tangelo	*Citrus X tangelo*	|
Cuban shaddock	*Citrus maxima*	|
Sweet lime	*Citrus aurantiifolia*	High
Stone fruit		Low
Almond	*Prunus dulcis*	|
Myrobalan plum	*Prunus cerasifera*	|
Apricot	*Prunus armeniaca*	|
Marianna plum	*Prunus domestica*	|
Shalil peach	*Prunus persica*	High

1/ Adapted from Maas (1990).

(d) Leaching for salinity control

(1) Salt balance and leaching

Where salinity is a hazard, the only economical means of salt control is to ensure a net downward flow of water through the crop root zone over time. In this case, the normally defined net irrigation requirement must be expanded to include an additional increment of water for leaching. The leaching requirement is the minimum fraction of the total applied and infiltrated water (irrigation plus precipitation) that must pass through the crop root zone to prevent a reduction in yield from excessive accumulation of salts (USDA 1954 and ASCE 1990).

Leaching occurs whenever the infiltrating part of the irrigation and rainfall exceeds the crop evapotranspiration and the water storage capacity of the soil. In humid regions precipitation is normally sufficient to adequately flush salts from the crop root zone. In arid regions additional irrigation water must be applied to assure adequate leaching. Depending upon the degree of salinity control required, leaching may occur continuously or intermittently at intervals of a few months to a few years.

Where a shallow water table exists, water may flow upward from the ground water resulting in poor drainage and preventing the export of salt from the root zone. This situation can be tolerated temporarily, but cannot be continued indefinitely. Upward flow and drainage may take place alternately during the year. Typically, drainage takes place in the winter and early in the irrigation season, when the crop evapotranspiration rates are low and rainfall or irrigation water applications are high. Upward flow often takes place late in the irrigation season when water requirements are high and rainfall and irrigation amounts are insufficient. If upward flow continues without sufficient leaching, soil salinity will ultimately reduce crop evapotranspiration so much that the crop dies. Temporary use of soil water beyond that normally removed between irrigations or from shallow ground water is a good water management strategy. However, where salinity is a hazard a net downward flow of water through the root zone is needed to sustain crop productivity.

Once salts have accumulated to the maximum tolerable limit for the crop under a given set of conditions, any salt added with subsequent irrigation must be balanced by a similar amount removed by leaching or salt precipitation to prevent a loss in yield. Two quantities generally are used to establish the leaching requirement:

- The salt concentration of the applied water.
- The salt tolerance of the crop (table 2–34).

The average salt concentration of the applied water can be calculated as a volume weighted value based upon the amounts of irrigation and precipitation. The crop salt tolerance, however, is more difficult to evaluate and has traditionally been established on a relative basis by measuring yields where water of varying salt concentration has been applied at relatively large leaching fractions (typically approaching 0.5). In some areas the electrical conductivity of the irrigation water varies throughout the growing season. A weighted average should be used to calculate irrigation requirements for salinity control in these areas.

(2) Leaching requirement

The most common method of estimating the leaching requirement uses a steady state salt-balance model. Hoffman, et al. (1990) and Rhoades and Loveday (1990) have defined the leaching fraction (L_f) for steady state conditions to be:

$$L_f = \frac{D_d}{D_a} = \frac{EC_{aw}}{EC_d} \qquad [2–71]$$

where:

D_d = the depth of drainage water per unit land area (in)

D_a = the depth of infiltrated water including both irrigation and precipitation (in)

EC_{aw} = the electrical conductivity of the applied water, irrigation plus precipitation (mmho/cm)

EC_d = the electrical conductivity of the drainage water (mmho/cm)

By varying the fraction of applied water that percolates through the root zone, the concentration of salts in the drainage water and either the average or the maximum salinity of soil water in the crop root zone (saturated-soil extract) can be maintained below the desired level. The leaching requirement (L_r) is defined as the minimum leaching fraction needed to prevent yield reduction and can be defined as:

$$L_r = \frac{EC_{aw}}{EC_d^*} \qquad [2–72]$$

where:

EC_d^* = the maximum value of the electrical conductivity of the drainage water without reducing crop yields

Inherent in equations 2–71 and 2–72 are the assumptions that no salts are precipitated, dissolved, or removed by the crop. Further, uniform areal infiltration of applied water and uniform evapotranspiration are assumed. Because the electrical conductivity of water is generally a reliable index of total salt concentration, it is often used to estimate the leaching requirement. Several empirical models have been used to relate EC_d^* to some readily available soil salinity value. Several of these empirical methods are given in table 2–39.

Water flowing into and out of the root zone rarely reaches a truly steady state. Thus the amount of salt in water stored in the root zone fluctuates continually. The goal of water management is to maintain the salinity within limits that neither allow excess drainage nor reduce crop growth. Nevertheless, a steady state analysis can provide an estimate of the extra irrigation water needed to maintain a favorable salt balance in the soil.

Table 2–39 Estimates of the electrical conductivity of drainage water for determination of the leaching requirements[1/]

Reference	Method used to estimate EC_d^* in equation 2–72
Bernstein, 1964	$EC_d^* = EC_e$ where yield is reduced 50%
van Schilfgaarde, et al. 1974	$EC_d^* = EC_e$ where roots can no longer extract water
Rhoades, 1974	$EC_d^* = 5\ EC_t - EC_i$
Hoffman and van Genuchten, 1983	Figure 2–33
Rhoades and Loveday, 1990	Figure 2–33

1/ EC_e = Electrical conductivity of the saturated-soil extract (mmho/cm).
EC_t = Crop salt tolerance threshold defined in equation 2–70 and values given in table 2–34 (mmho/cm).
EC_i = Electrical conductivity of the irrigation water (mmho/cm).
EC_d^* = Maximum value of the electrical conductivity of the drainage water without reducing crop yield (mmho/cm).

Procedures used to estimate the amount of drainage required to control leaching combine the above definition of leaching requirement (equation 2–73) and the soil-water balance. With soil-water conditions relatively high (normal irrigation scheduling practices), even small precipitation events can be effective in leaching excess salts. Under arid conditions with little rainfall, the combination of these two equations is straight forward.

However, in areas where growing season precipitation contributes substantially to the crop water requirements or off-season rainfall is a significant part of the leaching fraction, the procedure becomes more complicated.

The soil-water balance is used to determine the annual depth of irrigation water required. Over the course of the season, the beginning and ending soil-water balance is generally about the same when irrigation practices are used that refill the crop root zone each irrigation. With this assumption and the restriction that upward flow should not be included as a net water contribution in areas where salts are leached (i.e., adequate drainage), the amount of excess irrigation water required can be estimated. Under arid conditions, the following method is used to estimate the additional water contribution needed for leaching. The net irrigation requirement as a function of the leaching requirement is:

$$L_f = \frac{D_d}{D_a} = \frac{EC_{aw}}{EC_d} \qquad [2–73]$$

$$L_z = \frac{EC_{aw}}{EC_d^*} \qquad [2–74]$$

$$F_n = \frac{ET_c}{\left(1 - L_r\right)} \qquad [2–75]$$

$$F_g = \frac{F_n}{E_a} \qquad [2–76]$$

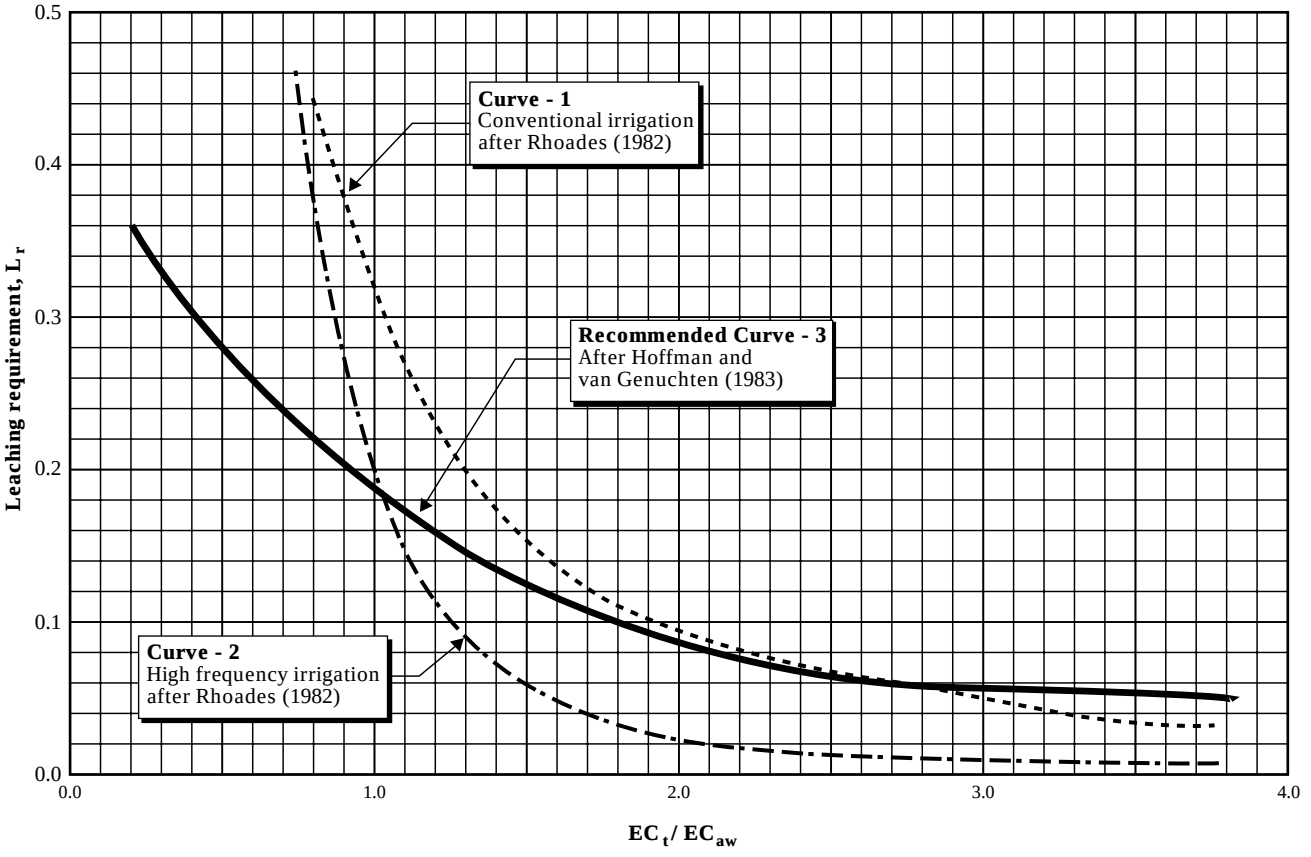
where;

F_n = The net irrigation requirement (in)
F_g = The gross irrigation application (in)
ET_c = The seasonal crop evapotranspiration (in)
L_r = The leaching requirement
E_a = The irrigation application efficiency (see section 623.0209 for definition of the irrigation application efficiency)

The leaching requirement (L_r) used in equation 2–75 is calculated from figure 2–33. The ratio of the electrical conductivity at the crop tolerance threshold EC_t (table 2–34) to the electrical conductivity of the applied water is calculated first. In this case, $EC_{aw} = EC_i$ as there is no rainfall. The net irrigation requirement can then be calculated using equation 2–75 and the gross irrigation requirement with equation 2–76 as shown in example 2–21.

Under growing conditions where significant precipitation occurs and must be included in the water balance, the following methods are recommended to determine the net irrigation requirement. In this case the electrical conductivity of the applied water must include the effect of rainfall. Determining the leaching requirement involves iteration because the leaching requirement depends upon the irrigation depth, and the irrigation depth is unknown.

Figure 2–33 Prediction of leaching requirement based on crop tolerance and water salinity (adapted from Hoffman and van Genuchten 1983)



The leaching requirement can be calculated by combining the equations for the soil-water balance and salt balance, giving:

$$F_i = \frac{ET_c}{1 - L_r} - P_{net} \qquad [2–77]$$

where:

F_i = The irrigation requirement (depth) that must infiltrate if all the infiltrated precipitation contributes to meeting crop evapotranspiration (in)

P_{net} = The average net annual precipitation that contributes to leaching

P_{net} can be estimated by:

$$P_{net} = P_a - SP_a - E_{os} \qquad [2–78]$$

where:

P_a = The average annual rainfall (in)

SP_a = The average annual surface runoff (in)

E_{os} = The average surface evaporation in the nongrowing season (in)

The average electrical conductivity of the applied water (EC_{aw}) can be calculated from:

$$EC_{aw} = \frac{EC_i F_i}{\left(F_i + P_{net}\right)} \qquad [2–79]$$

Example 2–21 Leaching requirement

Given: Irrigated area is in an arid location where rainfall is negligible. Tomatoes will be grown. The irrigation water has an EC_i = 2 mmho/cm. The seasonal evapotranspiration for tomatoes is 24 inches. Application efficiency is estimated to be 80 percent.

Required: Determine the leaching requirement and gross irrigation needed for this site.

Solution: L_r is a function of $\frac{EC_t}{EC_{aw}}$ (figure 2–33, curve 3)

Here, $EC_{aw} = EC_i$ and EC_t = 2.5 mmho/cm for tomatoes (table 2–34), so

$$\frac{EC_t}{EC_{aw}} = \frac{2.5 \text{ mmho / cm}}{2.0 \text{ mmho / cm}} = 1.25$$

From figure 2–33, $L_r \cong 0.15$

Then from equation 2–75:

$$F_n = \frac{ET_c}{1 - L_r} = \frac{24}{1 - 0.15} = 28.2 \text{ in}$$

Compute the gross irrigation requirement using equation 2–76:

$$F_g = \frac{F_n}{E_a} = \frac{28.2 \text{ in}}{0.8}$$

$$F_g = 35.2 \text{ in}$$

where:
EC_i = The electrical conductivity of the irrigation water

This equation assumes that the precipitation does not contain dissolved salts.

After the depth of irrigation that must infiltrate has been determined using equation 2–77, the following equation can be used to calculate the gross irrigation requirements:

$$F'_g = \frac{F_i}{\left(1 - F_{ro}\right)} \qquad [2–80]$$

where:
F'_g = The gross irrigation requirement to meet the salinity requirements (in)
F_{ro} = The fraction of the gross irrigation that does not infiltrate, decimal fraction

The value of F_{ro} is estimated from local experience and is a function of the type of irrigation system (sprinkler, border, furrow).

The irrigation requirement determined from the salinity balance and crop yield threshold (F_i in equation 2–77) is the depth of irrigation that must infiltrate to maintain a salt balance resulting in no yield reduction. It is not the net irrigation requirement. If the primary water losses during irrigation occur above the soil surface (because of evaporation, drift, or runoff), then the depth infiltrated is nearly equal to the net irrigation requirement. However, with some systems, significant amounts of deep percolation occur even when not trying to leach salts. This creates a problem when estimating the gross irrigation requirement. A method of predicting the gross irrigation requirement is to estimate the fraction of the gross application that does not infiltrate, then calculate the gross application using equation 2–80.

Equation 2–80 cannot be used without considering the seasonal water balance and the type of irrigation system. For example, a system could have such large deep percolation losses that adequate leaching occurs with a smaller gross irrigation than that needed to supply the seasonal evapotranspiration needs. The gross irrigation requirement should be computed based on both the seasonal water balance and the salt balance. The larger of the two gross irrigation amounts would then be the seasonal gross irrigation requirement.

The seasonal irrigation requirement to meet crop water needs is given by:

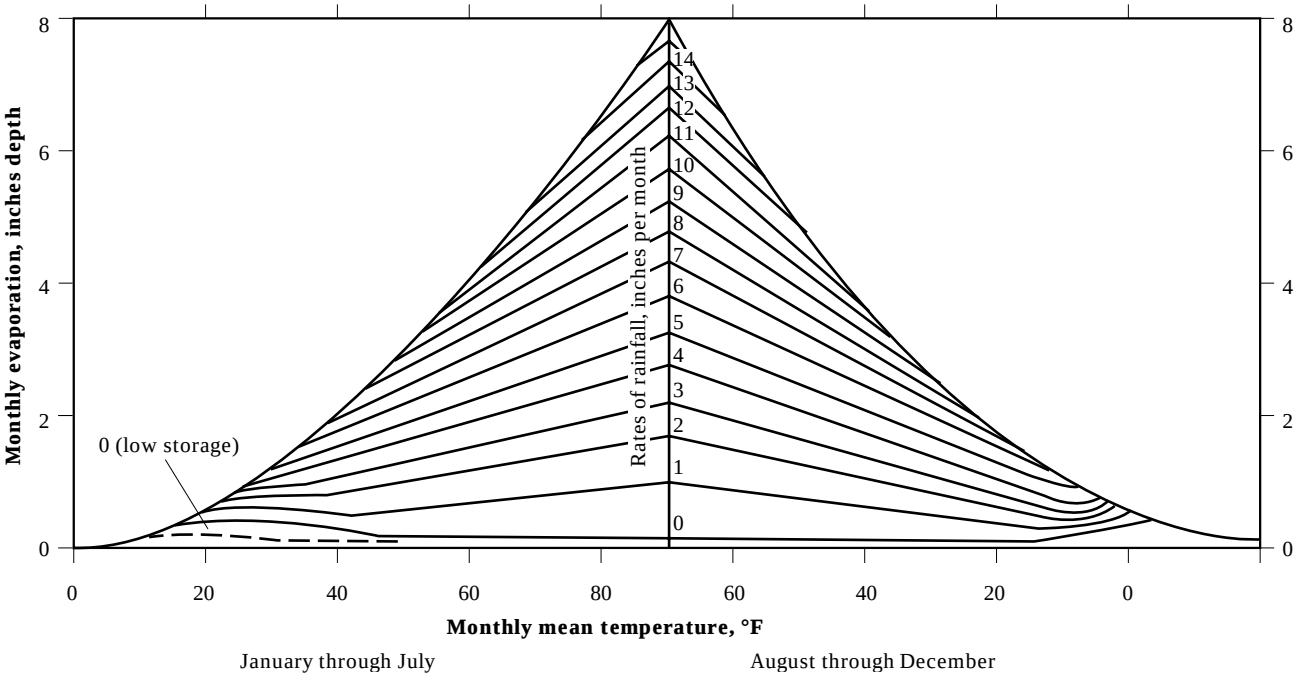
$$F_g = \frac{\left(ET_c - P_e\right)}{E_a} \qquad [2–81]$$

where:
F_g = Seasonal gross irrigation requirement (in)
ET_c = Seasonal crop evapotranspiration (in)
P_e = Growing season effective precipitation (in)
E_a = Irrigation application efficiency, decimal fraction (see section 623.0209 for definition and values)

The value of average annual runoff (SP_a) used in equation 2–78 must be determined locally. Where local information on evaporation from the soil during the nongrowing season is available, it should be used. If this information is not available, the information in figure 2–34 can provide a reasonable estimate. Care and judgment must be exercised in the use of the information in this figure because it is based on average soil and climatic conditions in the upper Midwest.

Because the electrical conductivity of the precipitation is essentially zero, a weighted average of the electrical conductivity of all water entering the soil must be used. This requires the use of a trial and adjustment procedure to determine the average annual leaching requirement. The trial and adjustment procedure is illustrated in the calculations in example 2–22.

Figure 2–34 Evaporation from land areas for various temperatures and rates of rainfall



Example 2–22 Leaching requirement calculations

Procedure to calculate leaching and gross irrigation requirements

1. Estimate L_r with figure 2–33 using the ratio EC_t/EC_i to that for EC_t/EC_{aw}.
2. Calculate F_i from equation 2–77.
3. Calculate EC_{aw} from equation 2–79.
4. Calculate EC_t/EC_{aw} and using figure 2–33 (curve 3) estimate a new value of L_r.
5. Repeat steps 2 through 4 until the value of L_r does not change.
6. Compute gross irrigation required (F_g') for salinity control using equation 2–80.
7. Compute gross irrigation required (F_g) for crop water use from equation 2–81.
8. Select the largest value for the gross irrigation from steps 6 and 7.

Given: Corn grown in Colorado

Seasonal consumptive use (ET_c)	= 24.8 inches
Average annual precipitation (P_a)	= 11.2 inches
Average growing season precipitation (P_t)	= 8.0 inches
Average annual precipitation surface runoff (SP_a)	= 1.0 inches
Average growing season effective precipitation (P_e)	= 6.0 inches
Surface evaporation in non-growing season (E_{os})	= 2.5 inches
Electrical conductivity of irrigation water (EC_i)	= 3.0 mmho/cm

Example 2–22 Leaching requirement calculations—Continued

Salt tolerance threshold of corn (EC_t from table 2–34) = 1.7 mmho/cm
Percent of gross irrigation that does not infiltrate (F_{ro}) = 10%
Irrigation efficiency = 70% (E_a = 0.7)

Find: The average annual gross irrigation requirement including the required leaching needs.

Calculation:

A. Determine the leaching requirement (L_r).

1. Use EC_t/EC_i to obtain an initial estimate of L_r;

$$\frac{EC_t}{EC_i} = \frac{1.7}{3.0} = 0.57$$

from figure 2–33, $L_r \cong 0.28$

2. Calculate F_i from equation 2–77 and P_{net} from equation 2–78:

$$P_{net} = P_a - SP_a - E_{os}$$
$$P_{net} = 11.2 - 1.0 - 2.5 = 7.7 \text{ in}$$

and $$F_i = \frac{ET_c}{1 - L_r} - P_{net} = \frac{24}{1 - 0.28} - 7.7 = 26.7 \text{ in}$$

3. Calculate EC_{aw} using equation 2–79

$$EC_{aw} = \frac{EC_i F_i}{\left(F_i + P_{net}\right)}$$
$$= 3.0 \frac{\left(26.7\right)}{\left(26.7 + 7.7\right)} = 2.33 \text{ mmho / cm}$$

4. Calculate EC_t/EC_{aw}

$$\frac{EC_t}{EC_{aw}} = \frac{1.7}{2.33} = 0.73$$

and from figure 2–33 (curve 3), $L_r \cong 0.24$.

5. Go to step 2 and repeat calculations, new F_i value:

$$F_i = \frac{ET_c}{1 - L_r} - P_{net} = \frac{24.8}{1 - 0.24} - 7.7 = 24.9 \text{ in}$$

6. New EC_{aw} value:

$$EC_{aw} = 3.0 \frac{\left(24.9\right)}{\left(24.9 + 7.7\right)} = 2.29 \text{ mmho / cm}$$

Example 2–22 Leaching requirement calculations—Continued

7. Determine ratio of EC_t to EC_w:

$$\frac{EC_t}{EC_{aw}} = \frac{1.7}{2.29} = 0.74$$

and from figure 2–33 (curve 3), $L_r \cong 0.24$.

8. Stop. L_r is about the same as that in step 4. Thus, F_i = 24.9 inches. Generally, the iteration only requires a few cycles.

B. Calculation of the gross irrigation requirement.

Equation 2–80 is used to calculate the gross irrigation requirement for salinity control:

$$F'_g = \frac{F_i}{\left(1 - F_{ro}\right)}$$

$$F'_g = \frac{24.9}{\left(1 - 0.1\right)}$$

$$F'_g = 27.7 \text{ in}$$

Without salinity control, the gross irrigation is calculated by equation 2–81:

$$F_g = \frac{\left(ET_c - P_e\right)}{E_a}$$

$$F_g = \frac{\left(24.8 - 6\right)}{0.7} = 26.9 \text{ in}$$

Thus, in the example, salinity control determines the gross irrigation requirements. Note that for this example the gross irrigation required for salinity control is only slightly above the "traditional" gross irrigation.

If soil-water depletions are replaced frequently, the plant roots near the soil surface will be exposed to water that has an electrical conductivity near that of the applied water rather than an "average" root zone value. Crop yields are, therefore, usually more affected by the irrigation water salinity level than by the soil-water salinity in the lower part of the root zone; particularly if the minimum leaching requirement is maintained under high frequency irrigation (see fig. 2–33, curve 2). Research findings (van Schilfgaarde, et al. 1974) indicate that leaching fractions generally can be much lower (in the range of 0.05 to 0.20) than those previously recommended by the U.S. Salinity Laboratory staff (USDA 1954). These reduced requirements contrast with estimated leaching fractions ranging from 0.30 to 0.60 for irrigated areas of the Western United States (Jensen 1975). In most areas this leached water percolates to drains or a shallow ground water zone where it ends up in return flow drainage.

Precise attainment of minimum leaching fractions is a difficult problem (van Schilfgaarde, et al. 1974). For example, a 1 percent error in estimating evapotranspiration can cause a 20 percent change in leaching if the leaching target is 5 percent. Willardson and Hanks (1976), in leaching tests with a solid set sprinkler system that applied water uniformly, concluded that it is unrealistic to expect to maintain average leaching fractions less than 0.10 to 0.15 on a field scale.

From a practical standpoint, the management approach to control salinity is more critical than an accurate estimation of the leaching requirement. If the management objective is to apply the calculated L_r to the 10 or 20 percent of the field that receives the least depth of water, the average L_r over the entire field will be considerably more than the estimated L_r. Jensen (1975) showed that, depending on the distribution uniformity and the management objectives, using a given L_r of the field receiving the least amount of water would produce an average L_r for the field three to five times higher than the given L_r, even for systems that have a very high uniformity. Also, because of the uncertainty in estimating the required depth of water to refill the profile, the achievement of a desired L_r over a field is difficult in practice. Periodic monitoring of root zone salinity is therefore unavoidable to verify the maintenance of salt balance. Irrigating without leaching for several seasons while monitoring the soil salinity status and then leaching periodically is often more practical.

To achieve the desired degree of leaching, either natural or artificial drainage must be adequate to convey the drainage water (leachate) away from the root zone. Moreover, if a water table is present, it must be controlled at an appropriate depth to enable leaching and to prevent any appreciable upward flow (with its salt) into the root zone.

The salt balance is affected by precipitation reactions involving slightly soluble salts, such as gypsum, carbonates, and silicate minerals. Consequently, the amount of salt leached below the root zone may be less than that applied. When irrigation water has a concentration of salt more than 100 ppm to 200 ppm and if leaching fractions are less than 0.25, some salts precipitate in the root zone and become stored in the soil profile. When irrigation water has a moderate amount of salt, such as the 800 ppm that occurs in the lower reaches of the Colorado River, and leaching fractions are below 0.25, salts precipitated in the soil profile exceed the amount weathered (Hoffman 1990). Salt precipitation may be a significant part of calculating the salt balance when the leaching fraction is small.

(3) Leaching frequency

High concentrations of salt in the lower part of the crop root zone can be tolerated with minimal effects in crop yield provided the upper part is maintained at a relatively low salt content. Plants compensate for reduced water uptake from the highly saline zone by increasing water uptake from the zone low in salinity. Although this compensation can occur without yield reduction, questions often asked are how much salt can be stored in the root zone before leaching is required and how frequently must extra water be applied to provide for leaching.

Some irrigation water has salinity at reduced levels such that even without leaching, many irrigations can be applied before salinity accumulates to levels detrimental to crop yield. This delay in leaching is dependent on crop salt tolerance. The more tolerant the crop, the longer the delay.

The salt tolerance of many annual crops increases as the growing season progresses. This suggests that if soil salinity levels are low enough at the beginning of the irrigation season for early seedling growth and adequate amounts of low-salt water are applied for evapotranspiration, soil salinity can be permitted to

increase throughout the irrigation season. For the next crop, rainfall either singly or in combination with dormant season or preplant irrigations can replenish soil water and leach accumulated salts to permit irrigation the next season without the need for further leaching. An important exception to this process occurs for perennial crops, like trees, that form their buds for the next year during the latter half of the irrigation season.

If irrigation water is saline, rainfall and out-of-season leaching may not be sufficient and leaching during the irrigation season may be required to prevent yield loss. The key factor is that leaching is not required until accumulated soil salinity surpasses the salt tolerance threshold for the crop. This certainly does not mean that leaching is relatively unimportant. The leaching requirement must be satisfied. Leaching can be done each irrigation or less frequently, such as seasonally or at even longer intervals, provided soil salinity is maintained below the salt tolerance threshold if yield losses are to be avoided. In many instances, inefficiencies of water application are compensated for by applying more water throughout the field. Where the leaching requirement is low, as with relatively nonsaline water, these additional applications frequently provide sufficient extra water for leaching.

(4) Influence of irrigation method

The irrigation method used to apply water affects the way salts accumulate in the crop root zone. Irrigation systems may not apply water uniformly over the entire irrigated area. Some irrigation methods apply water over the entire area by flooding and sprinkling. Furrow irrigation systems, porous or multiemitter trickle and subsurface irrigation systems apply water along lines. Point sources of irrigation water include microbasins and trickle systems that have widely spaced emitters. Soil salinity profiles beneath each method of irrigation may differ because of nonuniform water application over time and space.

Irrigation systems that apply water uniformly over the entire area typically result in a relatively uniform increase in salinity with soil depth to the bottom of the root zone, provided that net leaching is downward. If the field is inadequately drained where evaporation from the soil surface is high, soil salinity, particularly near the soil surface, increases with time between irrigations. Salt accumulation can also vary widely within a given field if soil hydraulic conductivity, uniformity of water application, or crop water extraction differ.

With surface irrigation methods (basin, borders, and furrow), the depth of applied water entering the soil varies with location in the field and depends on the soil infiltration rate and the time available for infiltration. Differences in the infiltration rate can be caused by land slope, degree of compaction, textural changes, and soil chemistry. The intake opportunity time may also vary. The upper end of the field nearest the water supply generally has water on the surface longer than does the lower end. High spots in the field also receive less water, and low spots more. Proper design and management of surface irrigation systems are critical when salinity is a problem.

A properly designed sprinkler system applies water with good uniformity and at application rates low enough to prevent runoff. If properly managed, it can result in adequate and uniform leaching. On sensitive crops, however, sprinklers can cause leaf burn when salts (sodium and chloride) concentrate excessively on the surface of leaves.

For buried trickle lines, the salt distribution within the soil profile is moved laterally and vertically. Typically, the salts concentrate in isolated pockets at the soil surface midway between line sources. A second, deep zone of accumulation whose location depends on the degree and efficiency of leaching also forms. The area directly beneath the line source is leached the most, with the size of the area determined by the rate and frequency of irrigation and the water extraction pattern of the crop. This type of soil salinity profile is common of many furrow and micro irrigation systems for row crops.

The salt distribution from point irrigation sources increases radically in all directions below the soil surface with the shape dependent on the rate of water application. In fine-textured soils, and particularly in layered soils, more water can move horizontally than vertically as the rate of application increases. This results in a relatively shallow depth of salt accumulation. For tree crops irrigated with several drip emitters per tree, the wetting patterns may overlap, thus reducing the level of salt accumulation midway between emitters under a tree.

Subirrigation, which has been adapted in a few select situations, is accomplished by managing the water table at an elevation to allow upward water movement of water to meet crop evapotranspiration demands. This process tends to concentrate salts on or near the soil surface irrespective of whether the salinity originates from the water or the soil. A similar process takes place with subsurface-trickle irrigation systems. Neither of these irrigation methods provide a means of leaching these shallow salt accumulations. Thus, care must be exercised when using these methods with poor quality water unless the soil is leached periodically by natural rainfall or surface applied water.

(e) Salinity management alternatives

(1) Salinity control

The major objective of improved management under saline conditions is to keep salinity within acceptable limits for germination, seedling establishment, and crop growth and yield while minimizing the salt-loading effects of drainage. Procedures that require relatively minor changes in management are selection of more salt-tolerant crops, additional leaching, pre-plant irrigation, and seed placement. Alternatives that require significant adjustments are changing the method of irrigation, altering the water supply, land-grading, modifying the soil profile, installing artificial drainage, and crop residue management. Ayers and Westcot (1985) and the ASCE Manual "Agricultural Salinity Assessment and Management" (ASCE 1990) give specific recommendations regarding these suggested management practices.

(i) More frequent irrigations—Salts in the soil solution concentrate as water is extracted by the crop. Hence, salt concentrations within the crop root zone are lowest following an irrigation and highest just before the next irrigation. Increasing irrigation frequency decreases the soil-water content variation thereby reducing the range of salt concentrations between irrigations. Maintaining a higher soil-water content provides water for plant use that is at lesser salt concentration. The upper part of the root zone remains relatively low in salinity if the depth applied at each irrigation is adequate to meet the crop water requirements. Frequent irrigations also permit small water applications that minimize surface runoff. Applying more water less frequently may not always be beneficial because the extra water is often lost to surface runoff or evaporation, which reduces the application efficiency. Frequent applications of a larger depth of water tend to reduce aeration in the soil. Water must pass through the crop root zone to be effective in leaching.

Notwithstanding the above, no improvement in yield under salinity caused by increasing irrigation frequency has been experimentally demonstrated (Bresler and Hoffman 1986). While the evapotranspiration rate does not decrease below its maximum potential until the allowable depletion is reached, the relative importance of the evaporation and transpiration components varies markedly with irrigation frequency. If the surface soil is wetted frequently, the evaporation rate is high even under full canopy conditions. Therefore, under frequent irrigations, the relatively high evaporation tends to concentrate salts in the surface layer, unless the soil is permeable enough to allow any excess water to leach below the root zone. In addition, root water extraction takes place preferentially from the upper soil layers if they are frequently wetted while extraction proceeds in the deeper layers only if the surface layer is allowed to dry excessively. Both processes tend to concentrate salts more in the surface layer under frequent irrigations, counteracting some of the benefits of a less fluctuating soil matric potential.

Thus, the recommendation to irrigate more frequently because of salinity must be tempered by other factors. An exception must be made for the case of micro irrigation, where the localized water applications displace the salts towards the boundaries of the wetted zone, leaving an area under the emitter that always has a higher water content and low salt concentration. Net water movement must be downward as well as laterally away from the plant. Too often micro irrigation systems are shut off during rainfall events, causing salt to move back into the area of plant roots because of the uniform rainfall application.

Increasing the quantity of applied water for salinity control is the only practical measure where a crop is irrigated with saline water. Studies have shown that increasing the seasonal irrigation depth compensates for the increased water salinity, at least up to a point, but the salinity of the irrigation water per se is not reduced (Bresler and Hoffman 1986).

(ii) Crop selection—If saline irrigation water is used, selection of a salt-tolerant crop may be required to avoid yield reductions. Agricultural crops have about a tenfold range in salt tolerance (table 2–34). The selection of a more salt-tolerant crop, however, will not eliminate the need for leaching and for better management practices; but it will reduce the need and amount of leaching. Planting crops earlier in spring or growing cool-season crops where salinity problems are marginal for production may reduce the water requirement sufficiently to attain full production even with rather salt-sensitive crops.

(iii) Additional leaching—Soluble salts that accumulate in excessive amounts in soils must be leached below the crop root zone. The time interval between leachings does not appear to be critical if crop tolerances are not exceeded. Depending on the size of the leaching requirement, leaching can be accomplished with each irrigation, every few irrigations, once yearly, or after even longer intervals, depending on the severity of the salinity problem and crop salt tolerance. An annual leaching during the noncrop or dormant period is often sufficient.

(iv) Preplant irrigation—Salts often accumulate near the soil surface during fallow periods, particularly if the water table is high or winter rainfall is below normal. Under such conditions seed germination and seedling growth can be reduced unless the soil is leached before the seed germinates.

(v) Seedbed preparation and seed placement—Obtaining a satisfactory stand of furrow-irrigated crops on saline soils or where saline water is used is often a problem. Growers sometimes compensate for poor germination by planting two or three times as much seed as would normally be required. In other instances, planting procedures are adjusted to ensure that the soil around the germinating seeds is low in salinity. Examples of the effect of bed shapes are shown in figure 2–35.

In furrow-irrigated soils, planting seeds in the center of a single-row, raised bed places the seeds in the area where salts are expected to concentrate. With a double-row, raised planting bed, the seed is placed near the shoulder of the bed and away from the area of greatest salt accumulation. Thus, soil salinity can be minimized at germination compared to single-row plantings because the water moves the salts away from the seed area toward the center of the ridge.

Alternate-furrow irrigation may help in some cases. If the planting beds are wetted from both sides, the salt accumulates in the top and center of the bed. If alternate furrows are irrigated, however, salts often can be moved beyond the single seed row to the nonirrigated side of the planting bed. Salts may still accumulate, but accumulation at the center of the bed will be reduced. The longer the water is held in the furrow, the lower will be the salt accumulation at the mid-bed seed area. Off-center, single-row plantings on the shoulder of the bed, close to the water furrow, have also been used as aids to germination under saline conditions. Double-row planting under alternate-furrow irrigation is not recommended because salt will accumulate on the edge of the bed away from the irrigated furrow.

Increasing the depth of water in the furrow of single- or double-row plantings, can also improve germination in salt-affected soils. Salinity can be controlled even better by using sloping beds, with the seeds planted on the sloping side just above the water line. Irrigation is continued until the wetting front has moved well past the seed row. During the first cultivation after planting, the sloped bed can be converted to a conventional raised bed.

(vi) Changing irrigation method—Gravity irrigation methods, such as basin, furrow, or border methods, generally are not sufficiently flexible to permit changes in frequency of irrigation or depth of water applied per irrigation and still maintain high levels of application efficiency. For example, with typical furrow irrigation, it may not be possible to reduce the depth of water applied below 3 to 4 inches per irrigation. As a result, irrigating more frequently might improve water availability to the crop, but might also waste water. If a change to more frequent irrigations is advisable, a sprinkler, drip, automated surface irrigation system may be required.

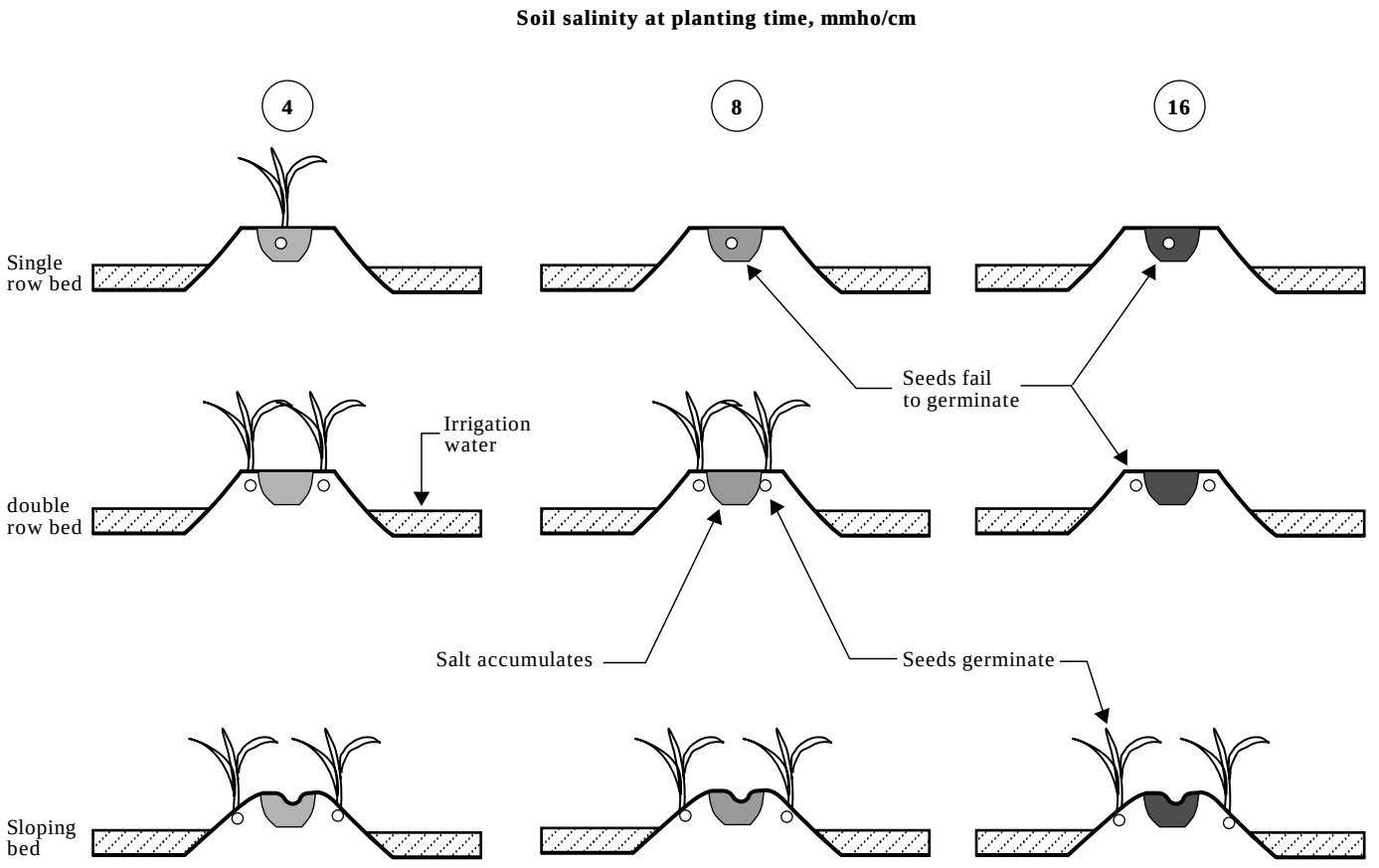
With adequate system design and management and by adjusting the duration and frequency of application, sprinklers can readily apply the depth of water to supply the crop's water requirement plus leaching. Sprinklers are sometimes used during germination and early seedling growth when some crops may be par-

ticularly sensitive to salinity, high temperatures, soil crusting, or a combination of these. Where the water quality is poor, yields may be better if drip irrigation is used because of the continuously high soil-water content and daily replenishment of water lost by evapotranspiration.

(vii) Changing water supply—Changing to a water supply of better quality is a simple solution to a salinity problem, but alternative supplies are not always available. If water of two different qualities is available, a blend may reduce the salinity hazard of the more saline water. However, this practice is not generally recommended (Rhoades 1990). Mixing water supplies may reduce the total volume of the water supply that can be consumed by salt-sensitive crops. The amount of such reduction depends upon the relative volumes and concentrations of the receiving water and wastewater and the tolerances of the crops to be irrigated. Therefore, the merits of blending should be evaluated on a case-by-case basis.

(viii) Land grading—In some instances fields are not graded accurately enough to permit satisfactory water distribution by surface irrigation. High spots in the field reduce water intake by the soil and may lead to salinity problems. As an alternative, sprinkler or drip irrigation can be used without precise grading.

Figure 2–35 Pattern of salt buildup as a function of bed shape and those effects on the germination of seeds placed at different locations on the beds (adapted from Bernstein, et al. 1955)



(ix) Soil profile modification—If the soil has layers that impede or inhibit root and water penetration, water management and salinity control can be simplified if the layers are fractured, destroyed, or at least rendered more permeable to roots and water. Subsoiling and chiseling may improve internal drainage of the soil profile, but results are often short lived. Deep plowing, however, often results in permanent improvement in some soils. It may bring up salt from the subsoil and create salinity problems. The physical and chemical properties of the entire profile should be considered before deep plowing is recommended. It generally is performed after land grading, but before leaching. This is a drastic treatment and often necessitates growing a salt-tolerant crop, such as barley, the first year after deep plowing, and then regrading.

The inhibiting layer may be caused by soil compaction from farming equipment and tillage operations. Where an inhibiting layer exists, it must be broken up by subsoiling or chiseling. It generally is possible to decrease the continuing severity of the problem by reducing farming operations that are not absolutely essential to produce the crop.

Salt and tillage break down soil aggregates and reduce the soil pore space, which reduce water movement and root development. The addition of organic matter to arid soils improves biological activity and water movement and results in a better soil condition. Reducing soil compaction and adding organic matter to arid soils are long-term beneficial modifications to the soil profile.

(x) Drainage—Lack of adequate surface or subsurface drainage greatly complicates water management for salinity control. Land grading and improved surface drainage systems may be required to alleviate poor surface drainage because flat or uneven slopes cause ponding and waterlogging. Subsurface drainage may be impeded by a layer that is slowly permeable to water. Subsurface drainage problems may also arise because of over-irrigation, seepage of water from higher elevations, or leakage from canals. A water table less than 4 to 6 feet below the soil surface may cause salts to accumulate in the root zone if net downward water movement is not maintained. Salt moves with the water to the soil surface and is deposited when the water evaporates. This can cause salinity problems even with good quality irrigation water. The salinity problem is solved by first improving drainage, then leaching.

(2) Management of infiltration problems

Both chemical and physical methods can be used to improve soil permeability reduced by excess sodium in the soil. Beneficial chemical methods include using soil or water amendments and blending or changing the irrigation water supply. Physical methods that may increase the amount of water penetration are increasing the irrigation frequency, cultivating or deep tilling, extending the duration of each irrigation, changing the grade or length of run for surface irrigations, collecting and recirculating surface runoff, using sprinklers to match the rate of water application to the soil infiltration rate, and using organic residue.

Amendments may be effective where the soil hydraulic conductivity has been decreased by the use of irrigation water low in salinity ($EC_i < 0.5$ mmho/cm) or by the presence in the soil or water of excessive amounts of sodium, carbonate, or bicarbonate (a high SAR). Amendments will not be useful if low hydraulic conductivity is caused by soil texture, compaction, water-restricting layers, or high ground water. Where low infiltration rates are caused by a high soil exchangeable sodium percentage (ESP), improved permeability should result if either the sodium concentration in the irrigation water is decreased or the concentrations of calcium, magnesium, or both, are increased. An inexpensive process or chemical is not available for removing sodium from irrigation water. Calcium, however, can be added to the soil or the water to decrease the sodium to calcium ratio. The source of calcium may be direct (gypsum) or indirect from acid or acid-forming substances (sulfuric acid or sulfur) that dissolve calcium from lime in the soil. Field trials should always be conducted to determine if results are sufficiently beneficial to justify the expense.

Where the permeability problem results primarily from a low water infiltration rate, granular gypsum may be more effective if left on the soil surface or mixed to a shallow soil depth, rather than worked deeper into the soil. Applying gypsum in the irrigation water generally requires less gypsum per unit area than that for soil applications. Water applications of gypsum are particularly effective for restoring lost permeability caused by low-salinity water, but the gypsum becomes less effective as the salinity of the irrigation water increases because it normally contains gypsum.

Sulfur may also be effective as a soil amendment for correcting a sodium problem (high ESP) if the soil

contains lime. The sulfur must first be oxidized to sulfuric acid by soil bacteria, which in turn reacts with soil lime to produce gypsum. The oxidation process is slow and requires a warm, well aerated, moist soil. Because sulfur is not water soluble and must react with soil lime, it is not normally effective as an amendment for improving water infiltration. Sulfur has been used successfully on calcareous soils that have an extremely high ESP level.

Sulfuric acid is used occasionally as an amendment and can be applied either to the soil or to the irrigation water. It reacts rapidly with soil lime because oxidation is not required. However, it is highly corrosive and dangerous to handle. If sulfuric acid is not handled properly, it may damage concrete pipes, steel culverts, checkgates, and aluminum pipes.

Fertilizer that has filler material can be used as a beneficial amendment. Other amendments may also be effective, but they are not extensively used because of their relatively high costs. Ayers and Westcot (1985), the U.S. Salinity Laboratory staff (USDA 1954) and ASCE (1990) give specific information on chemical methods to manage permeability problems.

Cultivation and deep tillage may increase water penetration, although in most cases they are only temporary solutions. Deep tillage (chiseling, subsoiling) can improve water penetration, but because many permeability problems are at or near the soil surface, the shallow soil soon reverts to its previous condition. Where slow infiltration is caused by a surface crust or a nearly impermeable soil surface, cultivation can roughen the soil and open cracks and air spaces that slow the surface flow of water and, for a time, greatly increase infiltration.

Long-term benefits of desired infiltration and permeability in the soil profile include:

- Reduce soil inhibiting layers by decreasing soil compaction from tillage and traffic.
- Add organic matter to improve biological activity, water movement, and maintain a better soil condition.

Extending the duration of each irrigation may increase the amount of irrigation water infiltrating, but aeration, waterlogging, excessive surface runoff, and surface drainage problems may result. The duration of the preplant irrigation could be extended to allow the soil profile to fill. This irrigation may provide the only opportunity to fill the deeper part of the crop root zone without secondary effects on the growing crop.

Crop residue left on the soil or cultivated into the surface often improves water penetration. For significant improvements in water penetration, relatively large quantities of crop or other organic residues are usually required. Rice hulls, sawdust, shredded bark, and many other waste products have been tried with various degrees of success at rates equal to 10 to 20 percent of the soil by volume. Nutritional imbalances and nitrogen shortages may develop after the use of sawdust, and chloride or potassium toxicity has been noted from the use of rice hulls.

(f) Reclamation of salt-affected soils

Reclamation is discussed separately from other salinity management techniques to emphasize the differences between the relatively continual management procedures required to control salinity and the reclamation procedures required to restore productivity lost because of severe soil salinity or sodicity. The U.S. Salinity Laboratory staff (USDA 1954) and ASCE (1990) give specific recommendations on the reclamation of salt-affected soils. Reclamation may require the removal of excess soluble salts as well as the reduction of soil ESP. The only proven way to reduce the soluble salt concentration in the root zone is leaching. The ESP is more difficult to reduce because sodium ions adsorbed on soil-exchange sites must first be replaced with divalent cations from the soil solution, through a chemical reaction, and then be leached from the root zone. Hence, the reclamation of a sodic soil is a combination of chemical and mass-transfer processes.

(1) Drainage

Reclamation of salt-affected soils by leaching requires adequate drainage because of the large amounts of water that must pass through the soil profile. Natural internal drainage is normally adequate if the soil profile below the crop root zone is permeable and provides sufficient internal storage capacity or if permeable layers are present to provide natural gravity drainage to a suitable outlet. Where such natural drainage is lacking, artificial systems must be installed.

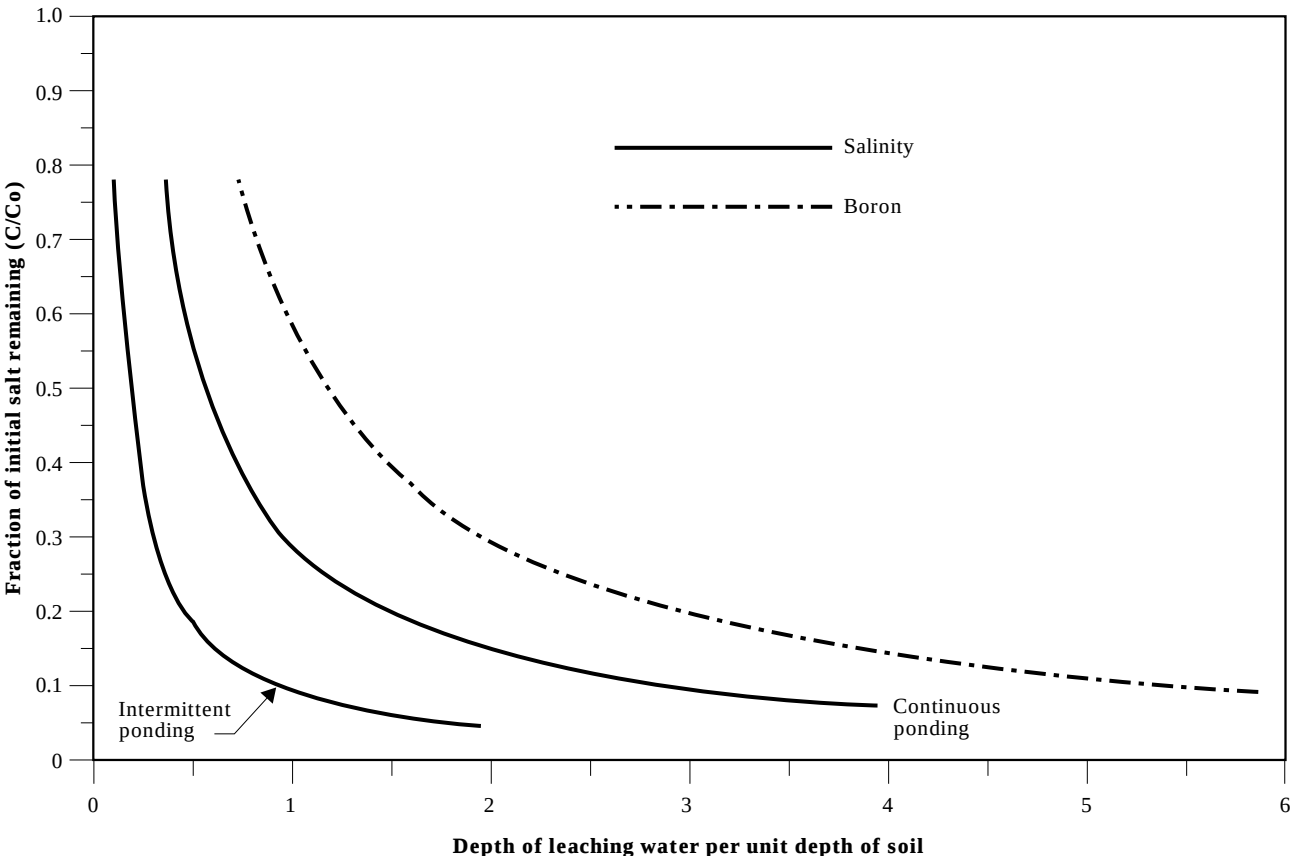
Preventing soil-water accumulation, either on the soil surface or in the plant root zone, requires continuous downward movement of water through the soil. In some cases, this excess water moves away through natural channels, such as porous subsoil strata, and eventually joins streams or rivers. In other cases artificial drains must be installed to make possible a net downward movement of soil water. The objective of drain installation is to lower and control the elevation of the water table. Specific information on the design of drainage systems is given in the SCS National Engineering Handbook.

(2) Removal of soluble salts

The amount of water that must be applied to reclaim a saline soil by leaching depends primarily on the initial soil salinity level and the technique of applying water. Typically, about 70 percent of the soluble salts initially present in a saline soil profile will be removed by leaching with a depth of water equivalent to the depth of soil to be reclaimed if water is ponded continuously on the soil surface and drainage is adequate. The relationship between the fraction of salt remaining in the profile and the amount of water leaching is shown in figure 2–36.

The amount of water required for leaching soluble salts can be reduced by intermittent applications of ponded water or by sprinkling. Differences in leaching efficiency among these methods primarily result from differences in the effect of molecular diffusion to primary flow channels and by the larger percentage of water flowing through the fine pores and soil mass in the unsaturated case. Leaching efficiency by sprinkling

Figure 2–36 Depth of water per unit depth of soil required to leach a saline soil by continuous or intermittent ponding, or to leach a soil inherently high in boron (adapted from Hoffman 1981)



is similar to that for intermittent ponding. Sprinkling has the added advantage over ponding in that precise land leveling is not required. Intermittent ponding or sprinkling may take longer than continuous ponding, but can be accomplished with less water.

Reclamation of salt-affected soils can be enhanced by the presence of plants. If the initial soil salinity is high, the topsoil must be leached before even salt-tolerant plants can be grown. The beneficial effects of plants are not well understood, but probably result from the physical action of plant roots, the increased dissolution of lime in the presence of carbon dioxide evolved from plants, or the addition of organic matter.

Excess boron is generally more difficult to leach than soluble salts because it is more tightly absorbed to soil particles. For soils inherently high in boron, the amount of water required to remove a given fraction of boron is about twice that required to remove soluble salts by continuous ponding. Boron leaching efficiency does not appear to be significantly influenced by the method of water application.

(3) Reclamation of sodic soils

Reclamation is more difficult for sodic soils than for saline soils. Three processes are needed to reclaim a sodic soil:

- An increase in the hydraulic conductivity.
- Leaching of the sodium salts from the system.
- Replacement of sodium by calcium.

During reclamation leaching water must percolate through the soil profile to dissolve and transport the divalent cations to the cation-exchange sites for exchange with the adsorbed sodium.

If sufficient gypsum is not naturally present, any soluble calcium salt can be applied as an amendment to reclaim sodic soils. The application of gypsum, calcium carbonate, or calcium chloride is most common. Sulfur and sulfuric acid are sometimes used to enhance conversion of naturally occurring calcium carbonate to gypsum, which is more soluble than calcium carbonate.

Calcium chloride is much more soluble than gypsum or calcium carbonate. When sufficient gypsum is naturally present in the upper soil profile and when the clay-sized minerals in the soil are of the 1:1 lattice or nonexpanding type (illite, kaolinite, vermiculite), chemical reclamation can be achieved simply by leaching if hydraulic conductivity is adequate. It may be advantageous in some cases, to superimpose a wetting and drying, freezing and thawing, or crop growth cycle on the chemical reclamation process before the soil is fully reclaimed. This is particularly true if soil permeability has been reduced drastically by exchangeable sodium. The amount of amendment required to reclaim a sodic soil is a function of the soil cation-exchange capacity (CEC), the desired change in ESP, the soil bulk density, and soil depth.

The flow of leaching solution through the profile is essential to the reclamation process. Hydraulic conductivity of a sodic soil is a function of both ESP of the soil and electrolyte concentration of the percolating solution as well as soil pH. Hydraulic conductivity decreases as ESP increases when electrolyte concentration remains constant, and increases as electrolyte concentration increases when ESP remains constant. The functional relationships vary with soil texture and mineralogy. The amount of water that must pass through the profile for chemical reclamation with gypsum depends on the amount of gypsum needed for chemical exchange.

Leaching solutions having low-electrolyte concentrations cause sodic soils to disperse, resulting in a low hydraulic conductivity. Leaching solutions having high-electrolyte concentrations have a flocculating effect on soil particles and cause clay packets to contract. As a result, the higher the salt concentrations of the leaching solution, the higher the hydraulic conductivity. Clay minerals having expanding-type lattices (montmorillonite) influence hydraulic conductivity more than do minerals of the nonexpanding type (illite, kaolinite, vermiculite).

Gypsum, sulfur, and limestone amendments generally are broadcast and then cultivated into the soil. If sulfur is used, leaching should be delayed until the sulfur has oxidized and gypsum has been formed.

If acids or acid-formers are used, alkaline-earth carbonates must be either in or above the sodic layer to ensure that downward percolating water will carry dissolved calcium to the exchange sites. After leaching, the solubility of gypsum in nonsaline, sodic soil is sufficiently low to be of no problem to any but the most salt-sensitive crops. Hence, if hydraulic conductivity is acceptable and sufficient leaching takes place,

crops that are not sensitive to sodium can often be grown during reclamation.

Where soil physical conditions have deteriorated and hydraulic conductivity is so low that the time required for chemical reclamation is excessive, the high-electrolyte method for sodic-soil reclamation may be warranted. This method consists of applying successive dilutions of a high-salt water containing divalent cations. Exchangeable sodium is replaced by divalent cations from the leaching solution, while water penetration is maintained by the flocculating effect of the high-salt water. Soil hydraulic conductivity often is extremely low where clay minerals of the expanding-lattice type (montmorillonite) are in the soil. The high-electrolyte method has also been used to reclaim a slowly permeable, mildly sodic, low-electrolyte soil in a humid environment where hydraulic conductivity and infiltration were increased by 30 to over 100 percent.

The U.S. Salinity Laboratory staff (USDA 1954) and ASCE (1990) give specific procedures and examples for reclaiming sodic soils.

In areas that have salt problems, irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive buildup of salts in the soil profile. Where subsurface drainage systems are installed to improve downward water movement and removal of the required leaching volume, the soluble salts can potentially move to surface water. Some soluble salts in drainage flows have been found to be toxic to waterfowl. Desirable nutrients necessary for plant growth that are also soluble, such as nitrates, are also easily leached out of the root zone.

Where possible, leaching events can be planned when nitrate levels in the soil are low. The leaching requirement for salinity control can be minimized with adequately designed, installed, and operated irrigation delivery and application systems and by monitoring irrigation applications and salinity levels. Drainage-return flows can be intercepted and diverted to other outlets and uses. Drainage flows can be desalted, disposed of through use of evaporation ponds, or used as a supply for applications where brackish water is acceptable, such as the irrigation of high salt-tolerant plants or other industrial uses (ASCE 1990, Doerge 1991).

623.0206 Auxiliary irrigation water requirements

In addition to the evapotranspiration and salinity management requirements, irrigation systems can meet special needs of crops. These secondary uses can often pay high dividends and should be considered in the design of irrigation systems. This section focuses on the water requirements for frost protection, crop and soil cooling, wind erosion control, and the application of chemicals through the irrigation system (chemigation). Water for these uses is generally required for a relatively short duration. The rate and timing of water application is often more important than the volume of water applied.

In some cases the primary and secondary uses for irrigation systems can be accommodated with one irrigation system design. In those cases the management of the system must change to successfully accomplish the secondary objectives. Information in this section describes some of the requirements for the auxiliary uses of an existing irrigation system.

The secondary benefit in some cases requires performance that an existing irrigation system or a system designed to meet evapotranspiration and leaching requirements cannot satisfy. In those cases a second irrigation system may be required. The design of the secondary system will be quite different from the system used to apply water for evapotranspiration and leaching. The design of an irrigation system to meet the auxiliary use often requires information not presented in this section. More specific references need to be consulted.

(a) Frost protection

Agricultural and horticultural plants are often produced in regions where cold temperatures can damage crops. If the plant temperature drops below the critical temperature where damage occurs, crop production that year may be lost on perennial species, and the entire planting may die on annual species.

Crop damage can result from two types of cooling. Radiant frost occurs in a clear, calm, dry environment where energy is radiated from the plant surface into the cold atmosphere. The ambient air temperature is generally above the critical temperature that causes plant damage, but outgoing radiation on clear nights may cool plants 1 to 4 °F below the ambient air temperature. In addition, crops withdraw energy from the air layer immediately surrounding the plants, thus air in contact with plants is generally cooler than the bulk air above the canopy. Light winds reduce the turbulence above the plants, allowing the plant surface to become colder than the air above. Frost forms on the plants when the temperature drops below the dew point of the air. This is called the critical temperature. The dew point is generally well below the critical temperature in dry environments.

An advective freeze occurs when the ambient air temperature drops below a critical value and high wind speeds increase the convective heat transfer from the cold air to the plants. Often the advective freeze is associated with the arrival of a cold front and occurs when wind speeds increase to above 10 mph. Irrigation can do little to protect plants from an advective freeze. In fact, wetting the foliage in an advective freeze can cool plants substantially, causing increased cold damage. Under windy conditions, the buildup of ice on plants and the irrigation system can cause structural damage as well. Thus, most cold protection is really for frost protection.

Some plant parts are more susceptible to damage from low temperatures than are other parts. Leaves, blossoms, and young fruit generally are the most sensitive to frost damage and are usually killed by a temperature of from 26 to 30 °F. Lethal temperatures of more hardy parts, such as buds of deciduous fruit trees, are related to stage of development. Therefore, the incentive to protect plants may be more at one time of the year than at another. Sometimes plants need to be cooled to delay bud formation early in the spring when a subsequent freeze is likely.

The processes involved in the phase changes of water must be understood to determine the irrigation required for frost protection. Water can exist as a vapor, liquid, or solid. Changing phases involves energy exchange. Evaporation requires about 1,080 BTU's of energy per pound of water at 32 °F. The reverse process is condensation, which releases energy (1,080 BTU/lb). To melt ice, energy must be added (143 BTU/lb), and to freeze water an equal amount of energy is

released. The final phase change is from a solid to vapor. Sublimation is where ice is transformed directly into water vapor without going through the liquid state. It requires about 1,220 BTU per pound.

What happens during a sprinkler application of water that provides frost protection? Consider an irrigation sprinkler operating while the air temperature is 33 °F. Water supplied to the irrigation system must be warmer than 32 °F, for example, 50 °F. After the water leaves the sprinkler nozzle, the water droplets begin to cool and evaporate. Cooling the droplets adds energy to the air. This is a primary way to use irrigation systems for freeze protection, but great care and large amounts of water are needed because only 1 BTU per pound is released for each degree Fahrenheit of temperature change of water. With time the water droplets will cool to the wet bulb temperature of the air, which is below 33 °F. If the water reaches the plant surface before dropping to the wet bulb temperature, it evaporates from the plant surface, drawing energy from the plant surface and dropping the plant temperature. If sprinkling only results in wetting the crop canopy so that evaporation occurs, the plants will be cooled below the ambient air temperature and sprinkling will actually damage the crop rather than protect it.

So what has to happen to provide protection? The processes that release energy, thereby warming plants and the air, include condensation and freezing. These processes must occur at a faster rate than the inverse processes of evaporation, melting, and sublimation. The irrigation system must be operated to provide that environment.

Coating plants with a water film can maintain the temperature above the critical plant damage point. Energy is lost from the outer surface of the water film by radiation, convection, and evaporation. The heat of fusion is released from the thin film as the water freezes. As long as the film is maintained, the temperature of the water will remain near 32 °F as freezing supplies the energy lost from the outer surface of the water film. The ice coating on the plant must be continually in contact with unfrozen water until the surrounding air warms enough so that the wet bulb temperature of the air is above the critical plant damage temperature. In California, ice-coated alfalfa plants were continually sprinkled at 0.11 inch per hour, and the plant temperature stayed above 28 °F. When the sprinkling was stopped, the sublimation of the ice dropped the plant temperature to 12 °F, 5 °F below the 17 °F air temperature. Sprinkling generally is required until the ice formed on the plants completely melts.

Several types of irrigation methods are available to protect plants from cold damage. Successful irrigation methods include overcrop sprinkling, undertree sprinkling, fogging, and flooding (Barfield, et al. 1990). Each process is somewhat different, and each has very special requirements.

(1) Frost protection from overcrop sprinkling

Barfield listed many of the cited successes and failures of frost protection. The results have been mixed, but overcrop sprinkler frost protection has been successful for small fruit, potatoes, flowers, cranberries, and grapes. Early research in frost prevention indicated that an application rate of about 0.1 inch per hour would protect crops against radiation frosts. Subsequent work showed that plants could be protected against freezing temperatures as low as 16 °F with zero winds where the application rate is increased to 0.25 inch per hour. At this application rate, protection was obtained under winds of 12 mph, down to 30 °F air and 9 °F dew point temperatures, respectively. Only 7 to 10 percent injury to mature strawberries was observed at these temperatures. In the check plots that were not irrigated, 100 percent of the mature fruit was injured.

The appropriate application rate for frost protection depends on several factors, and general recommendations are risky as evidenced by the list of failures of overcrop sprinkling in protecting crops. Yet the results from Gerber and Harrison (1964) provide an initial estimate of the required application rate for frost protection (table 2–40). These application rates were field tested in Florida under various temperature and wind speed conditions. The most practical rates range from 0.1 to 0.3 inch per hour. Repeat frequency of leaf or foliage wetting must be at least once each minute. Sprinkling must begin by the time the wet bulb temperature reaches 4 °F above the critical temperature of the plant parts to be protected. Once in operation, sprinkling must continue until the wet bulb temperature is back above the critical temperature by about 4 °F. Systems are generally operated until the plant is free of ice because of the rising air temperature. Recommended minimum temperature for turning on or off the irrigation system for frost control of apple trees in Washington is given in table 2–41.

Design considerations for overtree sprinkling to provide successful frost protection in Washington (USDA 1985) include:

- Plastic sprinklers have been used, but metal sprinklers seem to be preferred by growers.
- Under low temperature conditions, special frost sprinklers that have hooded springs and a special arm to reduce freeze up should be used.
- For good uniformity, pressure variation along the lateral should not exceed 20 percent of the design operating pressure of the sprinklers.
- The water supply should be protected from materials that might clog the sprinkler nozzles and against sand and silt particles that may abrade the nozzle openings. Frequent checks need to be made for proper sprinkler operation and any signs of nozzle clogging or wear. Systems should be checked for proper operation before they are needed. Sprinkler failure can result in severe damage or loss of crop. The frost protection system must be able to operate on a moment's notice in case of a rapid change in weather conditions. It must also be capable of operating for hours without interruption.
- Single nozzle sprinklers generally are used to minimize the amount of water applied. Nozzles range from 1/16 to 3/16 of an inch in diameter. Operating pressures generally range from 36 to 60 psi. Uniform application is important for good frost protection, efficient application of irrigation water, and fertilizers applied through the sprinkler system. SCS practice standards for sprinkler systems require that sprinkler spacing along the lateral not exceed 50 percent of the wetted diameter.
- Good surface and subsurface drainage is necessary to protect the crop against excess water.
- Heavy fall application of plant nutrients should be avoided to prevent their loss through runoff and deep percolation.

Table 2–40 Sprinkling rate (in/hr) necessary for frost protection [1/]

Temperature of a dry leaf, °F [2/]	Wind speed, mph [3/] 0–1	2–4	5–8	10–14	18–22
27	0.1	0.1	0.1	0.1	0.2
26	0.1	0.1	0.1	0.2	0.4
24	0.1	0.2	0.3	0.4	0.8
22	0.1	0.2	0.5	0.6	—
20	0.2	0.3	0.6	0.8	—
18	0.2	0.4	0.7	—	—
15	0.3	0.5	0.9	—	—
11	0.3	0.7	—	—	—

1/ Modified from Gerber and Harrison (1964).
2/ The temperature of a dry leaf is the expected minimum leaf temperature on an unprotected leaf. This ranges from 1 °F below air temperature on nights that have a light wind to 3 to 4 °F on very calm nights.
3/ **Note:** These rates are based on the assumption that relative humidity does not affect frost protection. Thus the rates should be used as a first approximation in determining the application rate for design and planning. The rates should not be used to manage an actual sprinkler irrigation system.

Table 2–41 Temperatures to start and stop overtree frost protection [1/]

Critical temperature (°F)	Dewpoint temperature range (°F)	Minimum turn-on or turn-off air temperature (°F) [2/]
32	3 to 10	45
	10 to 16	43
	16 to 21	41
	21 to 24	39
	24 to 28	37
	28 to 31	35
	31 to 32	33
30	0 to 9	42
	9 to 15	41
	15 to 20	38
	20 to 24	36
	27 to 30	32
28	0 to 8	39
	8 to 14	37
	14 to 19	35
	19 to 23	33
	23 to 27	31
	27 to 28	29
26	0 to 10	35
	10 to 16	33
	16 to 20	31
	20 to 24	29
	24 to 25	27

1/ Absolute minimum temperature for turning on or off the system (2 or 3 °F higher than the indicated minimum is recommended).
2/ Modified from the Washington State Irrigation Guide (WAIG 1985).

Experience and research have shown that overcrop sprinklers can be operated intermittently to provide frost protection while minimizing the amount of water that must be applied. The cycling frequency affects the water application rate and frost protection success. The foliage configuration of the plants, especially the amount of foliage overlap, has a significant effect. The part of the wetted area that receives water is also an important factor in selecting an application rate and cycle frequency. Perry, Martsolf, and Morrow (1980) developed a model to predict the allowable "off" time for cycling based on plant needs and environmental conditions. The model is quite complex and is not generally available for design at this time. However, it could be used in specific situations to improve designs to conserve water.

(2) Frost protection from undertree sprinkling

Barfield, Perry, Martsolf, and Morrow (1990) indicate that undertree sprinkling methods can also be effective in frost protection. Undertree sprinklers often produce small water droplets below the crop canopy, an area they termed "the misting zone." Here, the water droplets cool and evaporate. Thus, energy transfers from the water into the air surrounding the plants, thereby increasing the humidity of that air. If the humidification results in the formation of ice on the plants, energy is released, which can increase the degree of frost protection.

Evaporation of water from the soil surface can also enrich the humidity of the air, thus increasing the efficiency of undertree sprinkling. As the relative humidity is increased, the emissivity of the air decreases, reducing the outgoing longwave radiation and the degree of frost damage. The level of protection is dependent on the amount of water applied and the aerial extent of the freezing surface. Part of the heat from freezing and cooling of water is carried into the ground by infiltrating water. Another part goes into warming the air, and the rest into evaporation. Transfer of the heat of the frosty buds is by radiation, convection, and by condensation, which occurs on the coldest plant tissues. Ambient air temperature increases of about 2 °F are common although increases up to 4 °F have been found. Most of the systems use small (5/64 to 3/32 inch), low-trajectory (<7°) sprinkler heads at 40 to 50 psi. Application rates range from 0.08 to 0.12 inch per hour or slightly more than half of typical overtree requirements.

Although, undertree sprinkling appears to be quite promising, the physics of the process is not fully understood and the process has not been tested as extensively as overtree sprinkling. Davies, Evans, Campbell, and Kroeger (1988) developed a model to help predict the change of air temperature resulting from undertree sprinkling. Using their model, initial estimates can be made of the frost protection provided by undertree sprinkling. However, these results have been evaluated in only a few experiments. They proposed that additional testing of the procedure is needed before general design recommendations can be developed.

(3) Frost protection by fogging and flooding

Using fog generators for frost protection has had limited success. Fog can provide a radiation shield for frost protection by decreasing the amount of outgoing radiation that cools plants. To be successful, water droplets must be very small (about 10 microns in diameter). Such small drops cannot be produced with typical irrigation equipment. Fog must also be maintained in a thick layer, which is difficult to accomplish even with mild winds. The fog can also cause increased liability if the field is near a road.

Some frost protection occurs if the fog eventually freezes on plant surfaces. However, the rate of water application when fogging is generally quite low, providing less protection than sprinkling. Because sprinkled water must evaporate before condensing, fog that occurs from sprinkling offers no frost protection because of condensation. Thus, there is no net energy release. Equipment for fogging is expensive, difficult to operate, and may not be useful for irrigation. Thus, fogging appears to have limited potential for frost protection. Even if fogging is feasible for frost protection, methods to predict the required application rate and frequency for fogging are not readily available.

Flooding the soil surface can provide some frost protection for selected crops and locations. In some cases only the soil surface is wetted. The process seems to work because of increased evaporation from the soil leading to a more humid environment where condensation may be enhanced. Wetting the soil may also increase its ability to conduct heat to the soil surface, providing more short-term heating of plants. However, results have been mixed. In some cases crop damage is increased by flooding. In any case large

amounts of water may be needed, and significant lead time is required to provide enough water to flood the soil surface. The ability to flood the area limits the type of irrigation systems that are capable of providing frost protection.

Another frost protection practice is *delaying bud development*. In the fall deciduous trees enter a period of winter rest. In the spring buds begin growing, eventually leading to blossoming and leafing of the trees. Bud growth and blossom emergence are temperature dependent. Cool spring temperatures delay blossoming while warm temperatures accelerate bud development. A danger exists that premature bud and blossom development may be frozen if cold weather returns. Irrigation during warm periods early in spring may cool plant parts so that bud formation is delayed, thus avoiding later freezing of blossoms that emerge prematurely.

As with other frost protection practices, the results of evaporative cooling to delay bud formation have been mixed. Bloom delay has not been successful as a frost control measure on deciduous trees when water imbibition by the buds reduces the ability of the buds to super cool. In this case the critical temperature of the bud may be nearly the same as that of the bloom. Thus, even though bloom is delayed, little or no frost protection occurs. Sprinkled blossoms are often less winter hardy and more disease susceptible. Bloom delay has been successful for some coniferous trees, but the winter hardiness may be reduced.

Irrigation sprinkling devices must be operated to maintain the proper conditions to provide frost protection. Most experience deals with overcrop sprinkling. In the protection process, about seven times as much energy is used for evaporation as is released by freezing. Thus, for every unit of water evaporated, about seven units must be frozen to offset the energy loss. If inadequate amounts of water are applied, evaporation becomes dominant and plants rapidly approach the wet bulb temperature. The design and planning of irrigation systems for frost protection can be accomplished with existing guides; however, success requires close scrutiny and careful management of the irrigation system.

Weather forecasts provide a general alert to potential for frost, but they generally are not sufficiently site specific. Accurate temperature monitoring systems should be placed in good instrument shelters or radiation screens and used at plant level. Temperature alarm systems are a good idea to warn of impending dangerous temperature levels. Visual indicators are very important in determining the suitability of the irrigation application rate and frequency. Uniform ice formation on the plants provides a simple visual indication that more water is being applied than is immediately freezing. A clear rather than milky-white appearance of the ice provides additional evidence that the plant is not being refrigerated. Barfield, Perry, Martsolf, and Morrow (1990) discuss several other operational considerations for frost protection. Proper irrigation leads to plant protection with a minimum amount of water.

(b) Crop and soil cooling

Irrigation systems can also be used to cool plants, which can alleviate heat stress and delay bud development. The objective of this process is the opposite of frost protection, but same basic physics principles apply. In cooling, evaporation of water in the air and on the plant surface utilizes some energy that would otherwise be used for transpiration. In a normal environment plants can transpire adequately to maintain temperatures within a productive range. If the energy input becomes too high, the plants cannot meet the transpiration demand. The water potentials of plants decrease (i.e., become more negative) as water stress increases. If stress becomes too severe, the leaf water potentials may be reduced to growth limiting levels. The stress can normally be alleviated by adding water to increase the soil water potentials. However, on hot days heat stress may develop that limits growth even if the soil is wet and the soil water potential is near zero. Energy not used for transpiration is available to also heat the plants. Under these conditions the internal water status of plants improves only with reduction of the heat stress.

Using irrigation to cool plants and soil was reviewed by Barfield, Perry, Martsolf, and Morrow (1990). Yield or quality increases, or both, have been demonstrated for almonds, apples, beans, cherries, cotton, cranberries, cucumbers, flowers, grapes, lettuce, peas, potatoes, prunes, strawberries, squash, sugarbeets, tomatoes, and walnuts. Yield increases result from improved conditions for plant growth, reduced dehydration of fruit, fewer dropped blossoms, and less "burning off" of young seedlings at or near the soil surface.

The physical processes for cooling crops for heat suppression and showing phenological development are similar and relatively well understood (Barfield, et al. 1990). The required sprinkler application rate depends on the evaporative demand of the environment. The application rate should be adequate to keep the plant surface continuously wet during the desired period. Empirical relationships have been developed to provide practical guidance for plant cooling. Sprinkler irrigation can reduce ambient air temperature from 6 to 12 °F. Hobbs (1972) determined that the potential air temperature reduction during sprinkling with a solid set system (average application rates near 0.025 in/hr) can be estimated from three climatic parameters:

$$\Delta T = -0.282 - 0.193RH + 0.114T + 0.145U \qquad [2–82]$$

where:

ΔT = Estimated air temperature reduction, °F
RH = Prevailing relative humidity, %
T = Prevailing ambient air temperature, °F
U = Prevailing wind velocity, mph

Evaporative cooling from wet surfaces normally reduces leaf temperatures about 2.0 to 2.5 times the attained air temperature reduction. Crops can reach the wet bulb temperature of the air if the plant surface is uniformly and continuously wet. Soils are not cooled as extensively. The temperature near the soil surface is reduced to about half the air temperature reduction during sprinkling.

Very low application rates are adequate for cooling because of the high latent heat of evaporation of water. Application rates in reported studies have ranged from about 0.003 to 0.16 inch per hour. Maximum cooling occurs when sprinkling rates range from 1.0 to 1.5 times the prevailing potential evapotranspiration rate. Rates near the upper end of this range allow for inefficiencies caused by leaf runoff, nonuniformity of water application, and partial wetting of the leaf canopy. These rates are smaller than the typical application rate of sprinkler systems. Thus, typical systems may need modification or intermittent operation to cool the entire field adequately.

Continuous sprinkling during the heat stress period is necessary if application rates are near the potential evapotranspiration rate. Cycling sprinklers on and off every 10 to 15 minutes increases the efficiency of water use when application rates significantly exceed the potential evapotranspiration rates. Critical temperatures for initiating plant cooling are not well established. Sprinkling is usually begun at threshold temperatures near 80 to 84 °F for cool climate crops, such as potatoes, and at 86 to 90 °F for warm season crops. Cooling of soils for germination of critical crops, such as lettuce, has shown to be effective.

(c) Wind erosion control

Wind erosion can seriously damage young seedlings and reduce the long-term productivity of soils. Erosion occurs because of the shear force of wind over the soil surface. Soil particles are picked up and carried downwind or moved across the soil surface, sometimes at a high velocity. Where the soil particles collide with young plants, severe damage can occur. Once erosion begins the process is difficult to stop. Erosion primarily occurs where the soil surface is bare or mostly bare, smooth, and is in a loosened condition because of tillage or winter freezing and thawing. This occurs mostly from fall through spring, which is the nongrowing and early growth period of summer crops. Wind speeds are typically highest in the spring; therefore, wind erosion on sandy soils can be severe during seedling development of row crops. The seedlings can be physically damaged by wind, injured by sand blasting, or both.

Irrigation can help control wind erosion by increasing:

- The cohesion of soils to form surface crusts and clods.
- Plant growth and residue following harvest of an irrigated crop.
- Cropping intensity, which shortens the nongrowing periods on cultivated, irrigated cropland.

Little research data have been published that quantifies soil-water content versus erodibility under various soil textures, temperatures, and wind speed where water is applied for the sole purpose of wind erosion control.

Irrigation of medium- to fine-textured soils consolidates loose surface soils after drying and develops surface crusts that resist erosion. The cohesive forces from wetting restrict erosion while the surface is wet. However, as the surface dries, sandy soils resume their erodibility. On highly erodible, bare soils, erosion is

very difficult to control even with a continuous-moving sprinkler system. On warm, windy days evaporation of applied water is great enough that surface soil water is lost well ahead of the time the sprinkler irrigation system rewets the soil. Tillage following irrigation while soils are moist helps produce clods that are more resistant to wind erosion.

Irrigated crops harvested for grain, such as corn, sorghum, and wheat, produce more than adequate residue to control erosion. Generally, surface residue is adequate to protect against erosion as long as the residue remains on the soil surface during the wind erosion events and while growing crop cover is inadequate to protect the soil surface. Leveling or smoothing of irrigated fields by a land plane results in a loose, erodible surface soil condition. Many times it helps to roughen the soil surface by chiseling or other tillage, or by bedding for the next crop immediately after leveling or smoothing. The bedding operation increases surface clods. Also, the bed-furrow surface configuration is more erosion resistant than a flat soil surface, but only if the orientation of the beds/furrows is perpendicular to the predominant wind direction. Irrigation systems can also be used to establish winter cover crops. The cover crops develop adequate cover in the fall to protect the soil surface until the following cash crop is planted. They are especially useful for crops that leave little residue after harvest, such as soybeans, silage corn, sugarbeets, and potatoes.

(d) Chemigation

The application of chemicals (pesticides and fertilizers) through irrigation systems is defined as chemigation. Chemigation can produce positive economic and energy savings by reducing the number of field operations using ground equipment or airplane application systems (Threadgill, et al. 1990). Good system design operation and sound management must be used.

Irrigation water requirements for chemigation generally involve the required depth of water needed to apply the chemical.

The depth of application varies tremendously depending on the type of chemical used, the location of the target pest, number of applications of each chemical during the season, and if the chemical applications are a part of the overall irrigations or are in addition.

The chemigation system consists of a chemical injection device, an injection port, a chemical reservoir, a back flow prevention device, and a calibration device. The chemical injection device should be accurate within 1 percent of maximum injection rates and should be easily calibrated and adjustable for all chemicals at the required injection rates.

Calibration of injection systems and application of the chemicals in the irrigation water is extremely important. Constant rates of chemical injection is necessary during the application process. The rate can be calculated for continuous moving sprinkler systems as

$$\text{injection rate} = \frac{\text{planned chem. app. rate} \times \text{area irrigated}}{\text{time required to irrigate the field or set}}$$

The rate and volume of water applied during the chemigation process is generally the same as the irrigation rate and volume that is applied in the same time.

Chemigation has been widely used to apply fertilizer throughout the crop growing season. Fertigation has proved to be successful on automated systems, such as trickle and center pivots. In many cases, especially on sandy soils, the efficacy of the soluble fertilizers is improved by delaying fertilizer application until the plant uptake rates increase. Often, the peak crop water use and fertilizer uptake demands coincide, and few special irrigation water requirements are necessary.

Fungicides, insecticides, and nematicides have all been applied with irrigation systems. The efficacy and economics appear to be favorable, and farmers have endorsed the practice. These chemicals are much more toxic than fertilizers and some herbicides, and great care is necessary to protect the irrigator and the environment.

Sprinkler irrigation systems are well adapted to chemigation. All types of chemicals can be applied through these systems. Center pivot and lateral-move systems are particularly well suited because of their high uniformity of water application (coefficient of uniformity, CU). The CU for water applications from properly calibrated ground-based sprayers ranges from 0.5 to 0.9 (Bode, et al. 1968). Aircraft normally obtain CU values of about 0.7 (Yates 1962). Most types of sprinkler irrigation systems can be designed and operated to achieve a CU of 0.85 or above. However,

some solid-set and periodic-move sprinkler irrigation systems as well as traveling gun type systems will achieve CUs between 0.7 and 0.8. Continuously moving lateral systems, such as the center pivot, normally achieve a CU of at least 0.85 where installed. The higher CUs of moving systems make them ideally suited to chemigation.

Principle disadvantages of chemigation include:

- Chemicals may be needed when irrigation is not required.
- The threat of ground or surface water pollution increases if accidents occur or if anti-pollution devices fail on irrigation systems supplied from pumped wells.
- Sprinkler applications during windy conditions can result in reduced uniformity, a problem that is more severe with fixed and portable systems.
- Sprinkler drift may be excessive if wind speeds exceed 10 mph. Less than 5 mph is recommended.
- Wind can cause poor weed control on the leeward side of bed or hill planted crops.
- Chemicals can be deposited in nontarget areas because of wind drift and runoff from irrigation systems.
- Wettable powder forms of herbicide are difficult to keep in suspension during injection.

Chemical application with surface irrigation systems has also been successful; however, its potential is more limited. The application of water to the relatively shallow depths required for some chemicals is difficult, and deep percolation may occur more often than for sprinkler methods. Also, poor distribution uniformity can occur with surface irrigation systems that have too long of runs or for soils that have a high infiltration rate. Uneven infiltration may lead to nonuniform chemical distribution across the field. Tailwater reuse systems are necessary to recycle surface runoff to prevent contamination of surface or ground water. Many herbicides are absorbed on the soil particles, and the water distribution process under furrow irrigation may not transport herbicides from the irrigation furrow to the top of ridge or bed where weed control is needed. The turbulence in surface irrigation water can be inadequate to keep herbicides in suspension, leading to poor chemical distribution and a lack of weed control.

Threadgill, Eisenhauer, Young, and Bar-Yosef (1990) discuss in detail the requirements for successful chemigation practices. In many areas chemigation is highly regulated. Users must comply with local, State, and Federal regulations. As always, irrigators should carefully follow label directions. Irrigation systems properly maintained and calibrated should be used under watchful scrutiny to be safe and effective.

The State Cooperative Extension Service, chemical companies, and private consultants can provide localized specific recommendations.

(e) Plant disease control

High humidity or free water on plant foliage is often necessary for infection by fungus and bacterial diseases. Irrigation, especially sprinkling, changes the environment of the air and soil surrounding crops and could increase the occurrence of such diseases. Further, irrigation leads to increased plant densities compared to rainfed production, which can intensify disease problems. Sprinkler irrigation can spread disease organisms by droplet splash from infected plants and the ensuing movement of water over the soil surface if localized runoff occurs. Runoff from surface irrigated fields can transport disease organism across one field and into downstream locations. If disease organisms enter a canal system, diseases can be transported across multiple farms.

Diseases, such as bacterial blight on beans and leaf spot on sugarbeets, may increase in severity if irrigation is applied soon after rain or if applications are prolonged. In dense growing crops, irrigation can increase diseases of vegetable fruit in contact with the soil, such as fruit rot of tomatoes, strawberries, and melons; bottom rot of lettuce; and clerotinia rot of beans. The high humidity associated with low dense crops and wet soil condition is the disease-producing environment. Damage can be reduced by using wider rows or trimming plants to increase air movement between rows.

Root rots, such as rhizoctonia and verticillum, and fusarium wilts are not appreciably affected by irrigation in the normal range of soil water management, but may be more severe under excessive irrigation and under some stress conditions. Root pruning of sugarbeets caused by large shrinkage cracks develop-

ing in swelling clays can increase rhizoctonia infection by providing entry points into roots.

Some stalk rot infections, such as charcoal rot of sorghum (which reduces grain filling, causes premature senescence, and increases lodging), are increased by plant water stress during grain filling. Normal irrigation practices during grain filling generally provide adequate control of charcoal rot. Other physiologically induced disease problems associated with plant water stress that can be adequately controlled by irrigation are internal drought spot damage to potato tubers, blossom end rot of tomato, and black heart disease of celery. Diseases associated with irrigation are likely to be more widespread on vegetables and more severe in the humid, higher rainfall areas.

Treatment for disease may be thwarted by operation of the irrigation system. Sprinkler droplets can wash fungicide residue from foliage, requiring more frequent fungicide application. Wet soils following irrigation or impending sprinkler irrigations limit the times that spray applications can be applied by ground and aerial equipment.

Notwithstanding the above discussion, research and farming experiences generally indicate that irrigation induced bacterial and fungus infections are uncommon. Irrigations usually occur during warm and mostly clear weather; while, spore germination is favored by cool, cloudy, wet weather. Apparently irrigation does not provide the favorable microclimate effect long enough for major secondary infections to develop. In fact, results have shown that well managed irrigation can reduce some stress related diseases and physiological disorders. Proper management requires knowing the right amount of water to apply and when to apply the water. Knowledge of irrigation water requirements is essential to proper management.

(f) Seed germination

Each seed species must absorb a fairly definite proportion of water before germination will start. The amount depends on the structure, size, and composition of the seed. For example, minimum seed moisture content as a percentage of dry weight required for germination is about 30 percent for corn, rice, and sugar beets; 35 percent for peanuts; and 50 percent for soybeans.

Lack of oxygen in the atmosphere surrounding the seed retards germination. Poorly drained or saturated soils are low in oxygen content. Air movement in saturated soils is much slower than that in soils at field capacity level where the free water has drained. Excessive carbon dioxide in the air surrounding the seed also may result in seed injury.

For germination, soil should have a soil-water potential of not less than 12.5 bars for corn and 6.6 bars for soybeans. The soil-water potential must remain low for 5 to 8 days to ensure adequate moisture for the seed. Wide fluctuations in soil-water potential, especially above the critical levels, severely effects seed germination. The rate of root and shoot development of newly germinated seeds, like soybeans, is greater at lower soil-water potential. Pathogen organisms also develop on seeds and roots at very low soil-water potential (around 0.3 bars), and root growth can stop when soil-water potential approaches zero or near saturation. Some crops, such as corn, are less sensitive to high soil-water content and can germinate at levels just under saturation.

Salinity also adversely effects seed germination and root development. Most seedlings are less tolerate to higher salinity levels than they are as more established plants. Problems may occur after the seed is germinated and the hypocotyls from the seed encounter high levels of salts in the surrounding soil. Hypocotyl mortality occurs with crops that are sensitive to foliar salt damage. The levels of salinity that cause foliar damage in many plants from water spray vary from as low as 5 mmho/cm up to around 40 mmho/cm for tomato plants. Seedling roots are also sensitive to excessive salinity (see table 2–34). Mortality of the emerged seedling occurs when new seedling roots are exposed to soil water that has a high salt content. Maintaining a high soil-water content decreases salt concentration, thereby reducing root damage (Stanley, et al. 1961; Mederski, et al. 1973; Rhoades, et al. 1990).

623.0207 Effective precipitation

(a) Introduction

Precipitation stored in the crop root zone can be effectively used for crop evapotranspiration and thereby meet part of the crop's irrigation requirement. Precipitation in excess of the soil-water storage capacity percolates below the crop root zone. In some locations deep percolation is necessary to remove salts from the crop root zone and to maintain salinity levels in a range required for economical crop production. In areas that do not have salinity problems, deep percolation does not reduce irrigation requirements.

The contribution of precipitation to meeting the evapotranspiration requirements may be insignificant in arid areas and a major component in humid areas. To determine the irrigation water requirements of a crop, the part of the total consumptive use furnished by precipitation must be estimated.

(b) Definition of effective precipitation

Effective precipitation as used in this section is defined as the part of rainfall that can be used to meet the evapotranspiration of growing crops. It does not include surface runoff or percolation below the crop root zone. This contrasts with the conventional hydrologic definition where effective precipitation means that part of total precipitation that contributes to runoff. Further, the definition used here does not include that part of precipitation that contributes to leaching. Leaching is important in some areas and not in others. Therefore, the contribution of precipitation to leaching is handled in computing the leaching fraction rather than included in the effective precipitation definition.

(c) Processes controlling effective precipitation

Many pathways and processes are involved in determining the effectiveness of precipitation (fig. 2–37). Some evaporation that takes place in the atmosphere is rarely measured and is not included in normal precipitation records. Precipitation that passes through the atmosphere strikes either the soil or plant surface. Precipitation intercepted by vegetation is either retained on plant surfaces where it ultimately evaporates, or it drains to the soil surface. For either case, part of the precipitation may reduce crop evapotranspiration demands and is therefore effective.

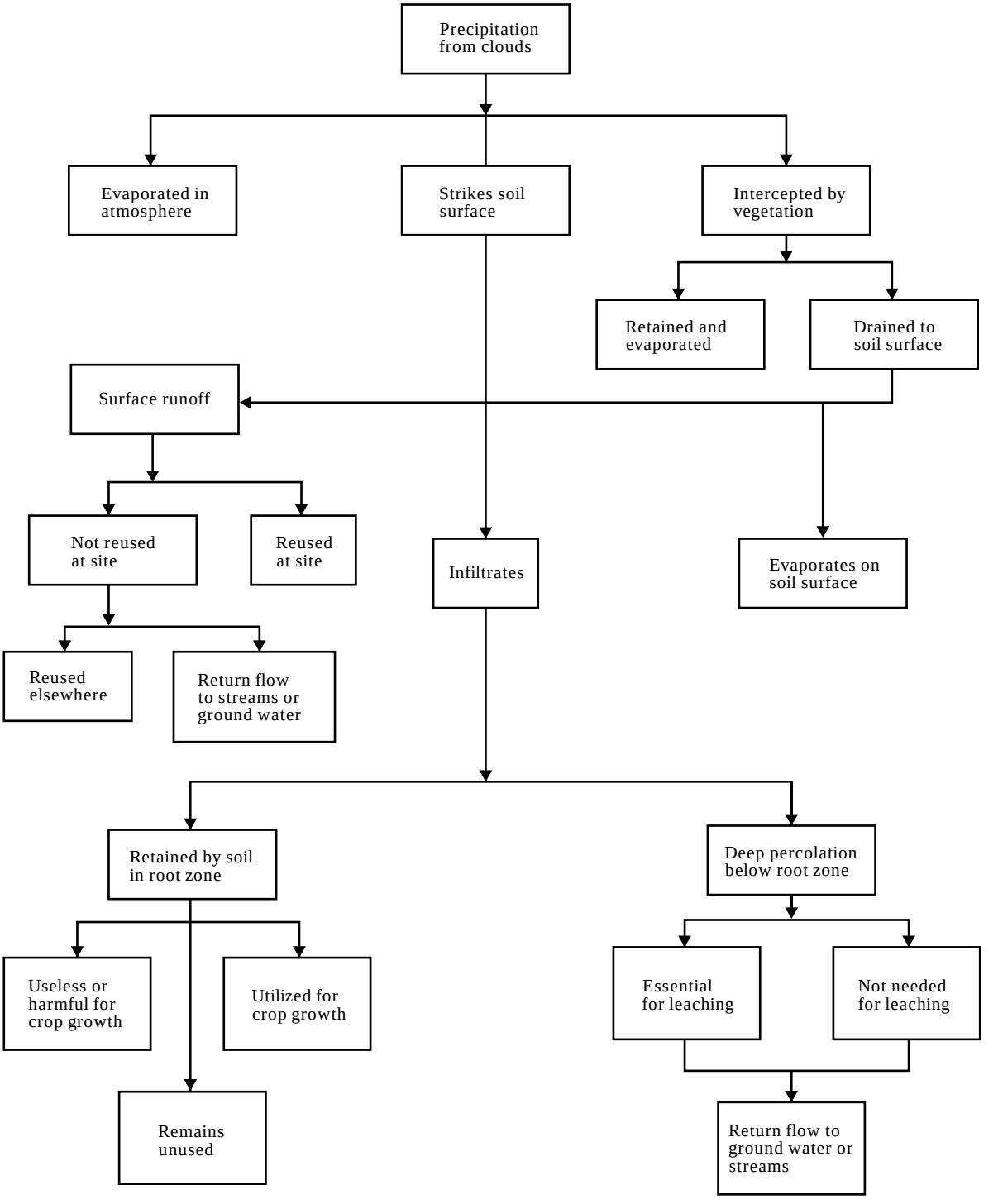
Water that strikes the soil surface, plus that draining to the soil surface from vegetation, may infiltrate, runoff, or remain in soil surface depressions and evaporate. After infiltrating into the soil surface, water can be stored in the crop root zone or percolate below it. Water retained in the crop root zone may be used for crop growth that season, or it may remain in the root zone for use during future growing seasons.

A fraction of the water that percolates below the crop root zone is useful, even essential, to remove salts in arid and semi-arid regions. The remaining component of deep percolation that is not needed for leaching can recharge underground aquifers or return to streams. However, these quantities of water do not reduce crop evapotranspiration and are not effective by the definition used here.

Some water that runs off the soil where it was received may infiltrate elsewhere in the field. If the infiltrated water remains in the root zone, it can be effectively used. Water that leaves the field is not effective.

Adequate measurements are seldom available to quantify the processes controlling precipitation effectiveness. Generally the controlling processes are so involved and the parameter data so uncertain or unavailable that simplified methods are developed and used to predict the fraction of precipitation that is effective. The processes included are rainfall, interception, infiltration, runoff, evapotranspiration, redistribution of soil moisture, and deep percolation.

Figure 2–37 Precipitation pathways (modified from Dastane 1974)



The methods used to estimate effective precipitation are based on representation and varying degrees of simplification of the hydrologic cycle. They vary depending on the level of analysis desired, such as project planning, drainage design, and such special conditions as a shallow water table and salinity management. The time step used in the measurement or calculation of effective precipitation must be carefully considered. An analysis that is sufficient for calculating the net irrigation requirements used in project planning is not the same as that needed for the real time estimation of effective precipitation required for irrigation scheduling. The estimation accuracy demanded for each need is much different.

(d) Factors affecting effective precipitation

Many factors influence the contribution of precipitation to crop evapotranspiration (table 2–42). Precipitation characteristics, soil properties, crop evapotranspiration rates, and irrigation management are the primary factors.

(1) Precipitation characteristics

The precipitation characteristics that determine the effectiveness are amount, frequency, and intensity. Each factor is extremely variable, both spatially and temporally, thus knowledge of these characteristics is essential in designing and managing irrigation systems.

Although some precipitation that evaporates from the plant or soil surface is effective in reducing crop evapotranspiration, the majority of effective precipitation must infiltrate into the soil and be stored in the crop root zone. High intensity rains, even of short duration, may exceed the soil infiltration rate and thus be less effective. Large rainfall events, even those of low intensity and long-duration may also contribute to substantial runoff and can cause deep percolation. Low-intensity, short-duration rains are generally the most effective.

The spatial distribution of precipitation also influences its effectiveness. Uniform rain over a field will raise the soil water content in a predictable way that can be included in future irrigation scheduling decisions.

Table 2–42 Factors influencing effective precipitation (modified from Dastane 1974)

Factor	Relevant characteristics
Precipitation	Depth, intensity, frequency, spatial and temporal distribution
Evapotranspiration	Temperature, radiation, relative humidity, wind speed, type of crop
Land	Topography, slope, type of land use
Soil	Depth, texture, structure, bulk density, salt and organic matter content, hydraulic characteristics
Soil water	Soil water content or potential, suspended matter, turbidity because of clay or colloids, viscosity, temperature, nature of dissolved salts
Ground water	Depth below soil surface, water quality
Management	Type of tillage, degree of leveling, type of soil management (terracing, ridging), use of soil conditioners
Channel	Size, slope, shape, roughness, backwater effect
Crops	Nature of crops, depth of root system, degree of ground cover, stage of growth, crop rotations

Nonuniform rainfall causes management tradeoffs and generally leads to reduced effectiveness. Because applying varying irrigation amounts across the field is not easy, the wetter areas of the field must receive the same irrigation amount as the drier areas. Thus, leaching occurs in the areas that received the most precipitation, and the effectiveness of the precipitation decreases.

The temporal distribution of precipitation also affects its effectiveness. Frequent rains generally lead to reduced effectiveness because the crop may not be able to use the supply as fast as the rain occurs. Infrequent rains provide time for the soil surface to dry (increasing infiltration rates) and for crops to extract soil water (reducing the chance of deep percolation).

The distribution of precipitation during the year and the regional climatic conditions greatly affect precipitation effectiveness. In arid areas where growing season precipitation is small, the moisture level in the soil profile when precipitation occurs is usually low enough so that most of the rain infiltrates and becomes available for crop evapotranspiration. Losses by surface runoff or percolation below the crop root zone are often negligible. Thus, the precipitation effectiveness in these areas is relatively high. For example, the Soil Conservation Service (SCS) estimated that the average precipitation effectiveness is 92 percent for Albuquerque, New Mexico, where the average total growing season precipitation is only 8 inches (USDA 1970).

In humid areas, rains of larger amounts and higher intensity occur more frequently during the growing season. These storms often produce water in excess of that which can be stored in the soil profile for later use. This excess water either runs off or percolates below the root zone. If the storm occurs soon after irrigation, almost all the precipitation is lost. Thus, in areas of high total growing season rainfall, the precipitation effectiveness is low as compared to that in arid areas. The SCS estimated that the average precipitation effectiveness is 64 percent at Baton Rouge, Louisiana, where the average total growing season precipitation is 39 inches (USDA 1970). In Florida, the growing season precipitation averages about 48 inches with an effectiveness of 55 percent (Jones, et al. 1984).

(2) Soil properties

Soil acts as a reservoir for the moisture supply to crops. Hence, properties of absorption, retention, release, and movement of water greatly influence the degree of precipitation effectiveness. Effective precipitation is largely determined by the soil infiltration rate and the available soil water storage. Both of these quantities depend on the soil water content. Dry soils have higher infiltration rates and larger available storage, thus they lead to more effective use of precipitation.

The infiltration rate of the soil is highly correlated to soil texture. Coarse textured soils, such as sands, generally have high infiltration rates leading to less surface runoff. Fine textured soils often have quite low infiltration rates, yielding substantial amounts of runoff.

If the water holding capacity in the crop root zone is high, the potential to store rainfall is high. This leads to effective precipitation. Conversely, if the soil water holding capacity is low, only part of some rains can be stored, which results in less effectiveness. The amount of water held and retained by a soil depends upon its depth, texture, structure, and organic matter content. Medium textured soils generally have the highest water holding capacity. The amount of soil water available to plants varies considerably. It ranges from 4 percent for coarse sands and 13 percent for clays to more than 20 percent for loamy soils. In addition, the deeper the crop root zone, the higher the precipitation effectiveness.

Antecedent soil water content also influences the amount of rainfall that can be stored in the crop root zone. Rainfall following an irrigation event reduces effectiveness. If soil water levels are maintained high by irrigation, precipitation effectiveness is lower than that for areas where more soil water depletion is allowed.

(3) Crop evapotranspiration

When the crop evapotranspiration rate is high, soil moisture is rapidly depleted. This provides more capacity for storing rainfall. If rain occurs, a large amount of water is required to reach field capacity, and losses because of runoff and deep percolation are small. Conversely, if evapotranspiration demands are small, the storage capacity for rainfall is provided at a slower rate and the capacity to receive water is less. If rain occurs, the runoff or deep percolation losses could be relatively large.

(4) Irrigation management practices

The net irrigation applied during each irrigation event is dependent upon the capacity of the crop root zone to store readily available moisture for plant use and the existing irrigation management practices.

Historically, irrigation systems were managed to refill the soil profile during each irrigation event. If a storm occurs soon after an application of irrigation water has been made, only a small percentage of the precipitation is needed to refill the profile and most of the precipitation is lost. Thus, the precipitation effectiveness may be low. If irrigation were scheduled such that small soil moisture depletions were maintained, a little soil water storage would be available to retain the rainfall. Conversely, if larger depletions were allowed, the available soil water storage would be greater, and the precipitation effectiveness would be higher.

Continuous-move irrigation systems, such as center pivots, and lateral-move systems have been operated to apply relatively small amounts of water each irrigation (generally less than 1.25 inches). If the irrigation scheduling procedures employed on the farm maintained a high soil water level or low depletions with frequent irrigations, the precipitation effectiveness would be low even for soils that have a high water holding capacity. Conversely, if the scheduling procedures maintain a relatively low soil water level or higher depletions using small, frequent, irrigations, the rainfall effectiveness is much greater. Thus, the type of irrigation system and the irrigation scheduling procedures used have a direct influence on precipitation effectiveness.

(e) Estimating effective precipitation

(1) Real-time estimates

Several irrigation management decisions require an estimate of the rainfall effectiveness on a real-time basis, often on a storm-by-storm basis. Perhaps the most common use of real-time estimates is for irrigation scheduling. When real-time estimates are needed, the amount of deep percolation and runoff must be estimated. The amount of effective precipitation for irrigation management is generally estimated using the soil water balance from equation 2–83

$$\Delta SW = P + F_g + GW - RO - D_p - ET_c - SD_L \qquad [2–83]$$

or as:

$$\Delta SW = P_e + F_n + GW - ET_c$$

with:

$$P_e = P - RO_r - D_{p_r}$$

and

$$F_n = F_g - RO_f - D_{p_f} - SD_L$$

where:

RO_r = runoff from rainfall
RO_f = runoff from irrigation
D_{p_r} = deep percolation from rainfall
D_{p_f} = deep percolation from irrigation
P_e = effective precipitation
ΔSW = the change in soil moisture storage in the crop root zone
P = total rainfall during the period
F_g = gross irrigation amount during the period
GW = ground water contribution during the period
RO = surface runoff during the period
D_p = deep percolation during the period
ET_c = crop evapotranspiration during the period
SD_L = spray and drift losses from irrigation water in air and off plant canopies

All of these quantities have the same units, volume per unit area, or units of length. They occur over a given time period Δt, which can range from daily to weekly for short-term estimates.

The upper limit of the soil water content for irrigation management purposes is limited by the field capacity. Thus the maximum amount of effective precipitation for an individual storm is the amount of soil water depletion at the time of the event. If the soil water balance is maintained on a daily basis using computer predictions, then the depletion at the time of the rain can be predicted. The value for each component of the soil water balance is updated daily to maintain an estimate of the soil water content.

The amount of runoff must also be estimated to predict effective precipitation. The runoff can be predicted using the USDA-SCS curve number method applied to the specific site. The water that does not run off must infiltrate. If all the infiltration is stored in

the root zone, the infiltration rate determines the amount of effective precipitation.

For a short time after a rain, the upward flow from the ground water is very small and can be ignored in estimating effective precipitation. Likewise an irrigation is seldom applied during significant rainfall events. The evapotranspiration can be estimated for the period to complete equation 2–83. Thus the only unknown in this equation is the effective precipitation, and it can be solved for by knowing the amount of runoff and the initial and final soil water contents. This procedure is commonly done in most good irrigation scheduling programs.

(2) Monthly effective precipitation

SCS scientists analyzed 50 years of rainfall records at 22 locations throughout the United States to develop a technique to predict effective precipitation (USDA 1970). A daily soil moisture balance incorporating crop evapotranspiration, rainfall, and irrigation was used to determine the evapotranspiration effectiveness. The resulting equation for estimating effective precipitation is: [2–84]

$$P_e = SF\left(0.70917 P_t^{0.82416} - 0.11556\right)\left(10^{0.02426\,ET_c}\right)$$

where:

P_e = average monthly effective monthly precipitation (in)
P_t = monthly mean precipitation (in)
ET_c = average monthly crop evapotranspiration (in)
SF = soil water storage factor

The soil water storage factor was defined by: [2–85]

$$SF = \left(0.531747 + 0.295164\,D - 0.057697\,D^2 + 0.003804\,D^3\right)$$

where:

D = the usable soil water storage (in)

The term D was generally calculated as 40 to 60 percent of the available soil water capacity in the crop root zone, depending on the irrigation management practices used.

The solution to equation 2–84 for D = 3 inches is given in table 2–43 and figure 2–38. For other values of D, the effective precipitation values must be multiplied by the corresponding soil water storage factor given in the lower part of table 2–43 or equation 2–85. For example, for an average ET_c of 7.6 inches, average precipitation of 4.7 inches, and soil water storage of 2.0 inches, the monthly effective precipitation is:

P_e = 3.70 in (from equation 2–84)
SF = 0.93
P_e = 3.70 x 0.93 = 3.44 in.

The average monthly effective precipitation calculated by equation 2–84 cannot exceed either the average monthly rainfall or average monthly evapotranspiration. If application of this equation results in a value of P_e that exceeds either one, the P_e must be reduced to the lesser of the two.

The procedures used to develop equations 2–84 and 2–85 did not include two factors that affect the effectiveness of rainfall. The soil infiltration rate and rainfall intensity were not considered because sufficient data were not available or they were too complex to be readily considered. If in a specific application the infiltration rate is low and rainfall intensity is high, large amounts of rainfall may be lost to surface runoff. A sloping land surface would further reduce infiltration amounts. In these cases the effective precipitation values obtained from equations 2–84 and 2–85 need to be reduced.

A recent comparison (Patwardhan, et al. 1990) of the USDA-SCS method (USDA 1970) with a daily soil moisture balance incorporating surface runoff highlighted the need for this modification. The authors concluded that the USDA-SCS method was in fairly good agreement with the daily water balance procedure for well drained soils, but overpredicted effective precipitation for poorly drained soils.

The USDA-SCS method is generally recognized as applicable to areas receiving low intensity rainfall and to soils that have a high infiltration rate (Dastane 1974). The method averages soil type, climatic conditions, and soil-water storage to estimate effective precipitation. This provides reasonable estimates of effective precipitation, especially for project planning. Further, the procedures were designed for a monthly time step. If additional detail is needed for a more thorough project analysis or for irrigation scheduling purposes, a daily time step would be required. In this case more sophisticated techniques can be used to estimate effective precipitation. Computer-based soil

moisture balance models incorporating new technology, including results from the current research thrusts in erosion prediction and infiltration modeling, can then be readily used to calculate effective precipitation.

While the current USDA-SCS method has several limitations, it is still a useful tool for the preliminary analysis of rainfall effectiveness if care is taken in its application. If daily estimates of effective precipitation are necessary, additional levels of analysis will require the use of a daily water balance with the attendant daily weather data requirements.

(3) Frequency distribution of effective precipitation

Crop evapotranspiration depends upon a number of climatic factors that vary from year to year. The variation of these factors is normally less than that in precipitation. Accordingly, the net irrigation requirement varies widely from year to year in response to changes in effective precipitation.

Because of this variation in net irrigation requirements, the development of an irrigation water supply cannot be based on average conditions. Estimates of

Table 2–43 Average monthly effective precipitation as related to mean monthly precipitation and average monthly crop evapotranspiration (USDA 1970) 1/

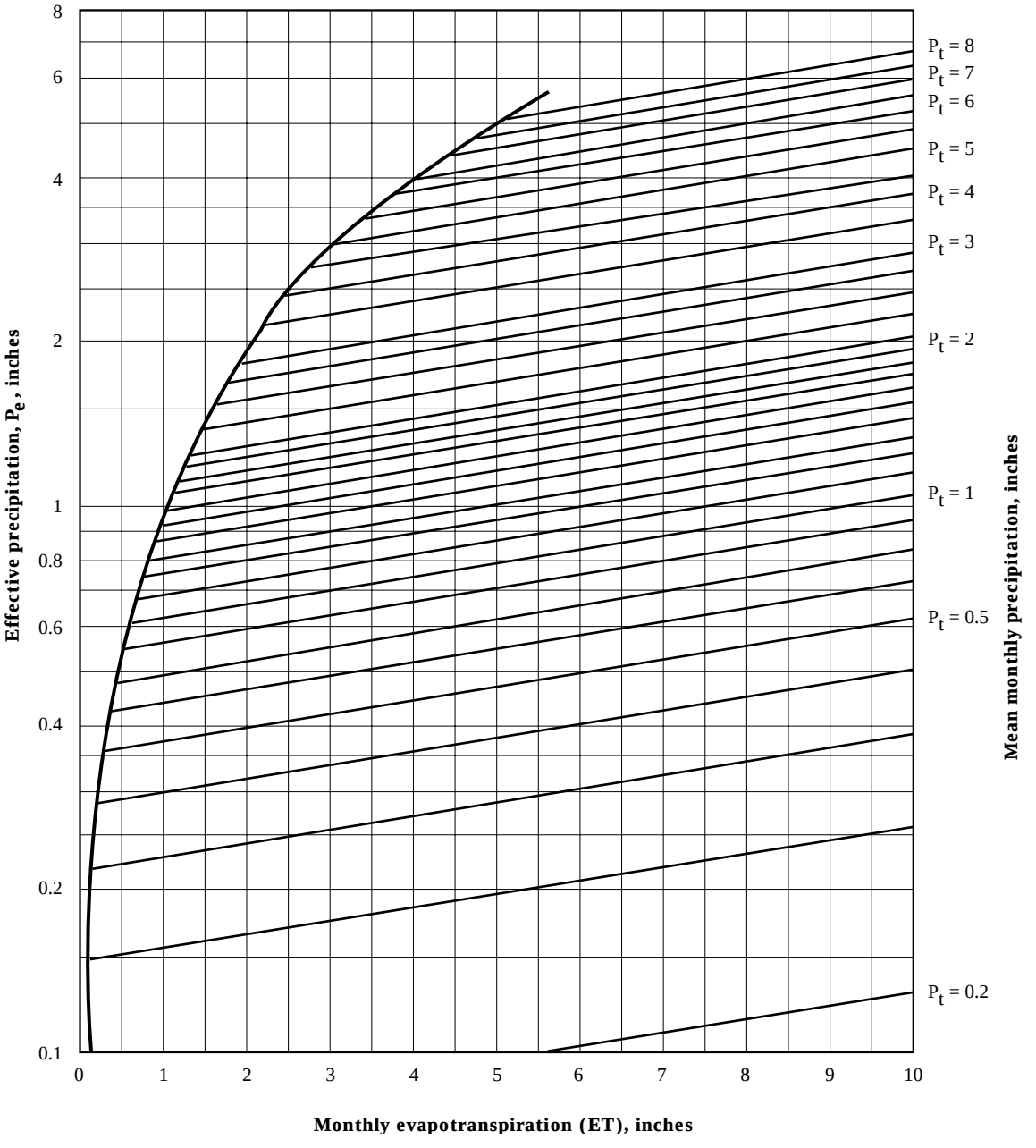
Monthly mean precipitation P_t (in.)	Average monthly crop evapotranspiration, ET_c (in.) 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	Average monthly effective precipitation, P_e (in.)										
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.45	0.47	0.50
1.0	0.59	0.63	0.66	0.70	0.74	0.78	0.83	0.88	0.93	0.98	1.00
1.5	0.87	0.93	0.98	1.03	1.09	1.16	1.22	1.29	1.37	1.45	1.50
2.0	1.14	1.21	1.27	1.35	1.43	1.51	1.59	1.69	1.78	1.88	1.99
2.5	1.39	1.47	1.56	1.65	1.74	1.84	1.95	2.06	2.18	2.30	2.44
3.0		1.73	1.83	1.94	2.05	2.17	2.29	2.42	2.56	2.71	2.86
3.5		1.98	2.10	2.22	2.35	2.48	2.62	2.77	2.93	3.10	3.28
4.0		2.23	2.36	2.49	2.63	2.79	2.95	3.12	3.29	3.48	3.68
4.5			2.61	2.76	2.92	3.09	3.26	3.45	3.65	3.86	4.08
5.0			2.86	3.02	3.20	3.38	3.57	3.78	4.00	4.23	4.47
5.5			3.10	3.28	3.47	3.67	3.88	4.10	4.34	4.59	4.85
6.0				3.53	3.74	3.95	4.18	4.42	4.67	4.94	5.23
6.5				3.79	4.00	4.23	4.48	4.73	5.00	5.29	5.60
7.0				4.03	4.26	4.51	4.77	5.04	5.33	5.64	5.96
7.5					4.52	4.78	5.06	5.35	5.65	5.98	6.32
8.0					4.78	5.05	5.34	5.65	5.97	6.32	6.68

1/ Based on 3-inch soil water storage. For other values of soil water storage, multiply by the following factors.

Water storage (D), in.	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
Factor (SF)	0.72	0.77	0.86	0.93	0.97	1.00	1.02	1.04	1.06	1.07

Note: Average monthly **effective** precipitation cannot exceed average monthly precipitation or average monthly evapotranspiration. When application of the above factors results in a value of effective precipitation exceeding either, this value must be reduced to a value equal the lesser of the two.

Figure 2–38 Average monthly effective precipitation as related to mean monthly rainfall and average crop evapotranspiration (based on 3-inch soil water storage)*



* For other values of soil water storage, multiply by the factors in table 2–43.

effective precipitation and irrigation water requirements generally are developed on a probability basis with the selection of a percentage chance of occurrence to use in design being an economic consideration. For example, providing a water supply that is adequate in 9 out of 10 years might be economical for high-value crops and only provide an adequate supply 6 out of 10 years for low-value crops.

A frequency distribution must be developed to use a probability basis to determine the appropriate depth of effective precipitation. However, the data for effective precipitation are seldom available. Therefore a method is presented to use the frequency distribution of total precipitation and the results from equations 2–84 and 2–85 to estimate effective precipitation.

To develop the frequency distribution, total precipitation records for a particular location are used to determine the total precipitation that occurred during the growing season for each year over a period of 25 years or longer. The growing-season precipitation totals are then ranked in order of magnitude and plotted on log-normal probability paper (fig. 2–39). A straight line that fits the data is then drawn. Instructions for plotting the points and drawing the frequency distribution line are in the SCS National Engineering Handbook, section 4, supplement A, part 3.18. An example of using log-normal graph paper is given in section 623.0210 of this chapter.

The frequency distribution shown in figure 2–39 provides an estimate of the probability that the total growing-season precipitation will be greater than a specified amount. For example, at Raleigh, North Carolina, there is an 80 percent chance that the total growing-season precipitation will exceed 14 inches. The average total growing-season precipitation is 17.9 inches at Raleigh (50% occurrence). The ratio of the total growing-season precipitation at 80 percent probability to the amount at the 50 percent probability (14/17.9 = 0.78) is used to adjust the average effective precipitation to what can be expected 80 percent of the time for the effective precipitation.

The monthly effective precipitation that would be expected for any frequency of occurrence can be estimated using figure 2–38 or table 2–43 if monthly consumptive use and monthly total precipitation for that frequency of occurrence are known. Example calculations of monthly and seasonal values of effective precipitation are shown in tables 2–44 and 2–45. The sample calculation in table 2–44 is for corn grown in North Carolina and that in table 2–45 is for alfalfa grown in Colorado.

The mean monthly ET_c and mean monthly total precipitation are determined in these tables. The average monthly effective precipitation is determined using table 2–43, figure 2–38, or equations 2–84 and 2–85. The 80 percent probable monthly precipitation for each month is determined by multiplying the average monthly precipitation by the previously determined ratio of the 80 percent probable to mean growing-season precipitation (i.e., 0.78 at Raleigh and 0.72 for Denver).

To determine the 80 percent probable effective precipitation, the mean monthly evapotranspiration and the 80 percent probable monthly total precipitation are used with equation 2–84 and 2–85 (or table 2–43 and figure 2–38).

Rainfall patterns may differ from month to month. Rather than using a constant ratio derived from seasonal or yearly data, the 80 percent probability rainfall should preferably be determined from a rainfall frequency distribution analysis prepared for each month using the method described above. This allows for a selection of rainfall probability for each month, with possibly a higher percentage when water is needed most, such as during the flowering stage of most crops. The calculations are similar to those given in tables 2–44 and 2–45 except for column 5.

Figure 2–39 Frequency distribution of growing season precipitation

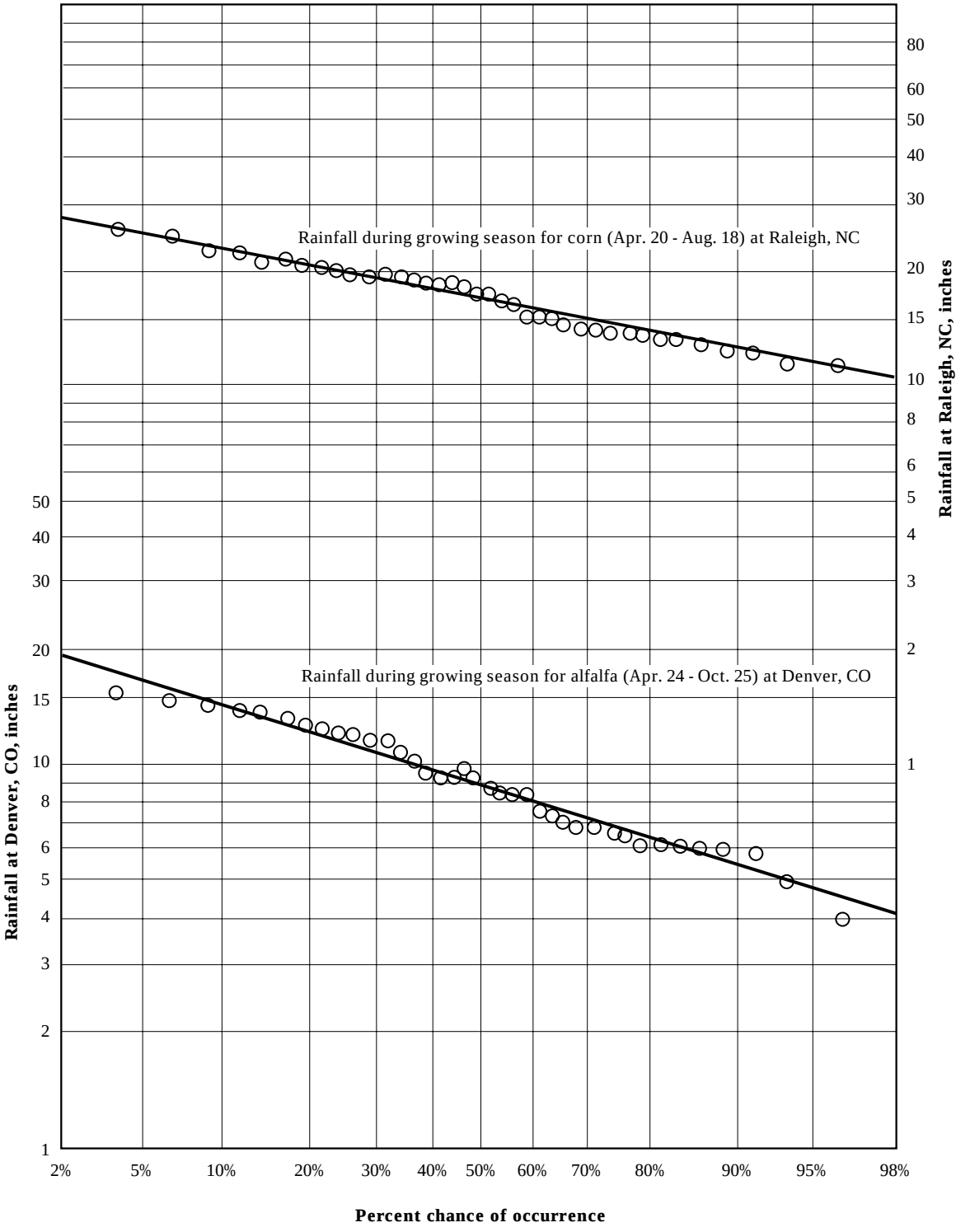


Table 2–44 Sample calculation of effective precipitation (corn at Raleigh, North Carolina)

Month 1/	Mean monthly ET_c (in.) 2/	Mean monthly rainfall (in.) 3/	Average monthly effective precipitation (in.) 4/	80% chance monthly precipitation (in.) 5/	80% chance effective precipitation (in.) 6/
April (20 days)	0.70	1.20	0.66	0.94	0.54
May	3.52	3.62	2.17	2.83	1.75
June	7.84	4.05	3.04	3.17	2.46
July	8.79	5.85	4.41	4.58	3.57
August (18 days)	4.10	3.15	2.18	2.47	1.76
Season totals	24.95	17.87	12.46	13.99	10.07

1/ Duration of the growing season.
2/ Crop ET_c values shown in this column are estimated from methods described earlier.
3/ Mean monthly rainfall values are taken from Weather Bureau records.
4/ Values of monthly effective precipitation are obtained using the values shown in columns 2 and 3 together with equations 2–84 and 2–85 (using net application depths of 2 inches for corn at Raleigh, NC, and 4.2 inches for alfalfa at Denver, CO). Values in equation 2–84 are for whole months only. To obtain a value for a part of a month, the values shown in columns 2 and 3 must first be converted proportionately to whole month values and equation 2–84 then used to obtain effective precipitation for the entire month. This later value is then converted back proportionately to obtain the effective precipitation for the actual number of days involved.
5/ Values of monthly precipitation for any frequency of occurrence are obtained by first plotting a precipitation frequency distribution curve (see figure 2–39) and then obtaining from the curve the value of the growing season precipitation for the desired frequency of occurrence, in this case, 8 out of 10 years (14.0 inches at Raleigh and 6.5 inches in Denver). This latter value divided by the average growing season precipitation (17.87 inches at Raleigh and 9 inches at Denver) will give a percentage factor (0.783 and 0.722, respectively) which, when applied to the values shown in column 3, will give the values of monthly precipitation shown in column 5 on a frequency basis.
6/ The values of monthly effective precipitation shown in this column are obtained by using the values shown in columns 2 and 5 together with equations 2–84 and 2–85. See comments in 4/.

Table 2–45 Sample calculation of effective precipitation (alfalfa at Denver, Colorado)

Month 1/	Mean monthly ET_c (in.) 2/	Mean monthly rainfall (in.) 3/	Average monthly effective precipitation (in.) 4/	80% chance monthly precipitation (in.) 5/	80% chance effective precipitation (in.) 6/
April (24 days)	0.57	0.49	0.33	0.35	0.24
May	3.99	2.70	1.93	1.95	1.44
June	6.36	1.44	1.24	1.04	0.91
July	7.80	1.53	1.43	1.11	1.05
August	6.66	1.28	1.13	0.92	0.82
September	4.00	1.13	0.87	0.82	0.63
October (25 days)	1.89	0.81	0.57	0.59	0.41
Season totals	31.27	9.38	7.50	6.77	5.51

See table 2–44 for footnote information.

(4) An alternative procedure

If the desired accuracy does not warrant the time required to gather the data to determine the growing season precipitation frequency distribution curve for each crop under consideration, an alternative procedure may be used. This procedure involves multiplying an average ratio to the average growing season effective precipitation to obtain the growing season effective precipitation for a given percent chance of occurrence. The average ratio varies with the desired percent chance of occurrence and with average annual precipitation as shown in table 2–45.

Again, using corn grown North Carolina as an example, it is desired to find the growing season effective precipitation that will have an 80 percent chance of occurrence. Average total annual precipitation at Raleigh is 46 inches, and the average growing season effective precipitation for corn has been determined as 12.5 inches (table 2–44). Table 2–46 gives the average ratio applicable to effective precipitation at this probability level as 0.842. Thus, the growing season effective precipitation that may be expected to occur or be exceeded in 8 out of 10 years would be 0.842 x 12.5, or 10.5 inches. This compares to 10.1 inches that is calculated in table 2–44 using a monthly approach.

Example 2–23 illustrates the use of table 2–46 to estimate the effective precipitation during the growing season.

The frequency distribution of effective precipitation for months or other short-time periods may be determined by applying the same ratios shown in table 2–46.

Table 2–46 Average ratios applicable to effective precipitation

Average annual rainfall (in.)	- - - - - - - Probability of occurrence - - - - - - -				
	50	60	70	80	90
3	0.80	0.68	0.56	0.45	0.33
4	0.84	0.72	0.61	0.50	0.38
5	0.87	0.76	0.65	0.54	0.42
6	0.88	0.78	0.68	0.57	0.45
7	0.89	0.79	0.69	0.60	0.48
8	0.90	0.81	0.71	0.62	0.51
9	0.91	0.82	0.73	0.63	0.53
10	0.92	0.83	0.75	0.65	0.55
12	0.93	0.85	0.78	0.69	0.58
14	0.94	0.86	0.79	0.71	0.61
16	0.95	0.88	0.81	0.73	0.63
18	0.95	0.89	0.82	0.74	0.65
20	0.96	0.90	0.83	0.75	0.67
22	0.96	0.90	0.84	0.77	0.69
24	0.97	0.91	0.84	0.78	0.70
26	0.97	0.92	0.85	0.79	0.71
28	0.97	0.92	0.86	0.80	0.72
30	0.97	0.93	0.87	0.81	0.73
35	0.98	0.93	0.88	0.82	0.75
40	0.98	0.94	0.89	0.83	0.77
45	0.98	0.94	0.90	0.84	0.78
50	0.98	0.95	0.91	0.85	0.79
55	0.99	0.95	0.91	0.86	0.80
60	0.99	0.95	0.91	0.87	0.81
70	0.99	0.95	0.92	0.88	0.83
80	0.99	0.95	0.92	0.89	0.85
90	0.99	0.96	0.93	0.90	0.86

Example 2–23 Using table 2–46 to estimate the growing season effective precipitation

Determine: The growing season effective precipitation that will occur or be exceeded in 8 out of 10 years at a site where the average total annual precipitation is 30 inches and the average effective precipitation for a growing season is 12 inches.

Solution: Reading across from average annual rainfall = 30 inches, the applicable ratio is 0.81. Thus, the 80 percent probability growing season effective precipitation is 0.81 x 12 = 9.72 inches.

(f) Carryover soil moisture

Recharge of soil water because of rainfall during the off-season can reduce the annual irrigation requirements. However, this contribution of carryover soil moisture resulting from winter rain and snow events to the seasonal water requirements is difficult to estimate. In some areas winter precipitation is sufficient to bring the soil moisture in the crop root zone to field capacity. This is particularly true in humid areas where the custom is to deduct the readily available moisture (equivalent to the net irrigation application) when estimating seasonal net irrigation requirements. Therefore, in humid areas, the root zone can be depleted to a dry condition late in the irrigation season with the anticipation of off-season recharge. The stored soil-water contribution in this case is the mature crop root depth times the percentage depletion at the end of the growing season.

In semi-arid regions, the winter precipitation may be inadequate to completely recharge the crop root zone before the start of the irrigation season. In this case, the amount of effective precipitation during fall, winter, and spring must be predicted. This quantity represents the long-term stored soil-water contribution to the net irrigation requirements.

Where late-season water supplies are short (generally arid areas), the soil moisture is often well below field capacity and possibly down to the wilting point in the fall. Under these conditions a pre-irrigation may be required because of the limited system capacity, inadequate rainfall, and perhaps excessive depletions from past growing seasons. Often these irrigations are the largest application of the season and can be quite wasteful. In these conditions the stored soil-water contribution to the net irrigation requirement is generally quite small.

In areas that have saline irrigation water, the stored soil-water contribution is generally small because of the leaching requirement and the necessity of maintaining a net downward water movement. Also the effects of salinity generally increase rapidly as the soil-water content drops. Therefore, the contribution of stored soil water to the irrigation requirement is generally small for areas that have salt problems.

For crops that have a 4-foot root zone, the amount of usable water that could be stored can range from 1 to 2 inches of water per foot depth of soil, or between 4 to 8 inches in the 4-foot root zone. This can be a major part of the annual requirement of some crops and can be supplied by winter precipitation in some areas in wet years. In areas where irrigation water is plentiful, it is not unusual to find the soil moisture content at the end of the season nearly as high as that at the beginning. No storage capacity is left in the root zone in these areas, and the contribution from winter precipitation is negligible. Nevertheless, the quantity of moisture carried over in the soil from winter precipitation tends to offset any deficiency in the estimated irrigation water requirements.

623.0208 Water table contribution

(a) Introduction

Methods to predict estimates of upward flow rates from a water table are presented in this section. The soil parameters required for these procedures are quite variable and may require field data for specific sites. Field monitoring should be used to ensure that values for soil properties are appropriate and that crop performance meets expectations. Upward flow from a water table can be used to meet the irrigation requirements. In the presence of a shallow water table, it can be a significant part of the irrigation requirements.

A water table near the crop root zone can supply part of the crop evapotranspiration requirements without reducing production. Generally, the rate of water supply is greatest where the distance between the bottom of the crop root zone and the water table is relatively small. However, if the water table remains too close to the soil surface for long periods of time, a lack of aeration in the root zone may develop and limit crop production. Determining the necessary drained depth has been widely researched and depends on soil, climate, and crop factors. Wesseling (1974) gives a preliminary discussion of the effect of wet soils on crop production. Drainage is beyond the scope of this chapter and is well documented in other sources, such as part 624 (section 16) of the SCS National Engineering Handbook. The purpose of section 623.0208 is to determine the amount of water provided to a crop by capillary rise from a water table.

The amount of upward flow from a water table can be important especially in areas where the required irrigation rate is small because of rain or because climatic demands are small. In areas where salinity is a problem, leaching is necessary to remove salts from the crop root zone. This water, high in salts, should not be returned to the crop root zone by upward flow.

The rate that water can be transferred from a water table to the crop depends on the characteristics of the soil, the water content of the root zone, and the depth of the water table. The movement of water through an unsaturated section of soil depends on two soil properties—the capillary pressure head (h) and the hydraulic conductivity (K). The capillary pressure head, caused by the soil's attraction for water by capillarity, is the soil-water potential or soil moisture tension expressed as a positive value in units of length. The hydraulic conductivity is derived from Darcy's Law of waterflow in the soil:

$$q = -K(h)\frac{\partial h}{\partial z} + K(h) \qquad [2–86]$$

where:

- q = volume of waterflow per unit area of soil, commonly called the soil-water flux
- $K(h)$ = hydraulic conductivity, a function of pressure head h
- h = capillary pressure head
- z = distance, expressed as depth below the soil surface

The flux has units of velocity such as inches per day.

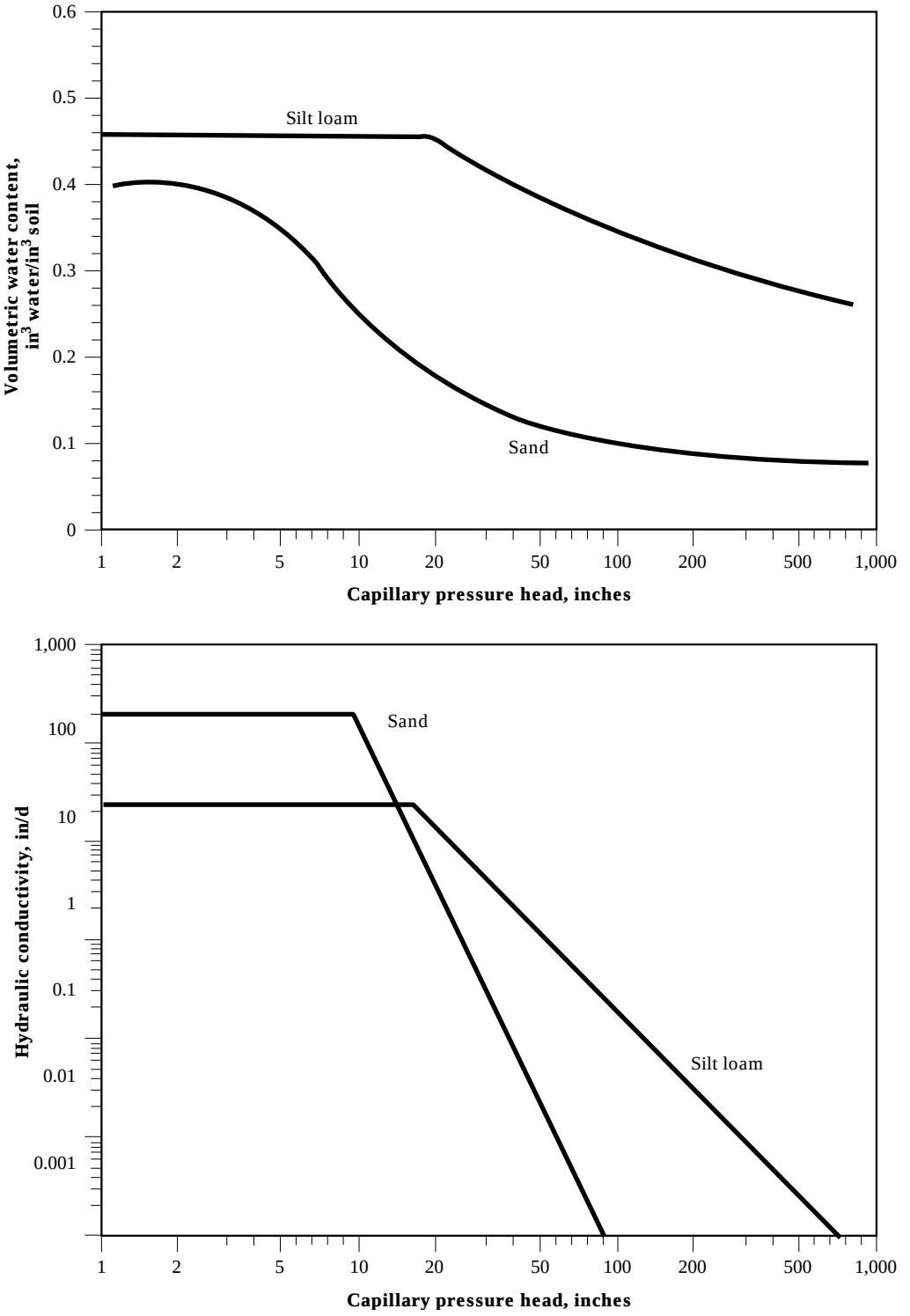
The dependence of the hydraulic conductivity and volumetric moisture content of the soil on the capillary pressure head is illustrated in figure 2–40. The hydraulic conductivity of unsaturated soil decreases rapidly as the soil-water content decreases below saturation. Several types of functions have been proposed to describe the relationships among hydraulic conductivity, volumetric water content, and capillary pressure head. Raats and Gardner (1974) give more information on the subject. One method that has worked well for soils that have a moisture content above field capacity was developed by Brooks and Corey (1964). They described the volumetric water content by:

$$\theta_v = \theta_r + (\theta_s - \theta_r)\left(\frac{h_b}{h}\right)^{\lambda_p} \qquad [2–87]$$

where:

- θ_v = volumetric water content
- θ_r = residual volumetric soil-water content defined by Brooks and Corey (1964)
- θ_s = saturated volumetric water content
- h_b = capillary pressure head at the bubbling pressure
- h = capillary pressure head
- λ_p = pore size distribution index

Figure 2–40 Hydraulic properties for sand and silt loam



In the Brooks and Corey method, the residual soil-water content, bubbling pressure, and pore size distribution index are empirically determined for a given soil. The hydraulic conductivity is given by:

$$K = K_o \left(\frac{h_b}{h} \right)^{\eta} \qquad [2–88]$$

where:
K = hydraulic conductivity
K_o = saturated conductivity
η = an empirical parameter equal to:

$$\eta = 2 + 3\lambda_p \qquad [2–89]$$

Darcy's Law illustrates that vertical, unsaturated waterflow upward into a root zone is affected by the capillary pressure head, gravity, the hydraulic conductivity, and the depth from the root zone to the water table.

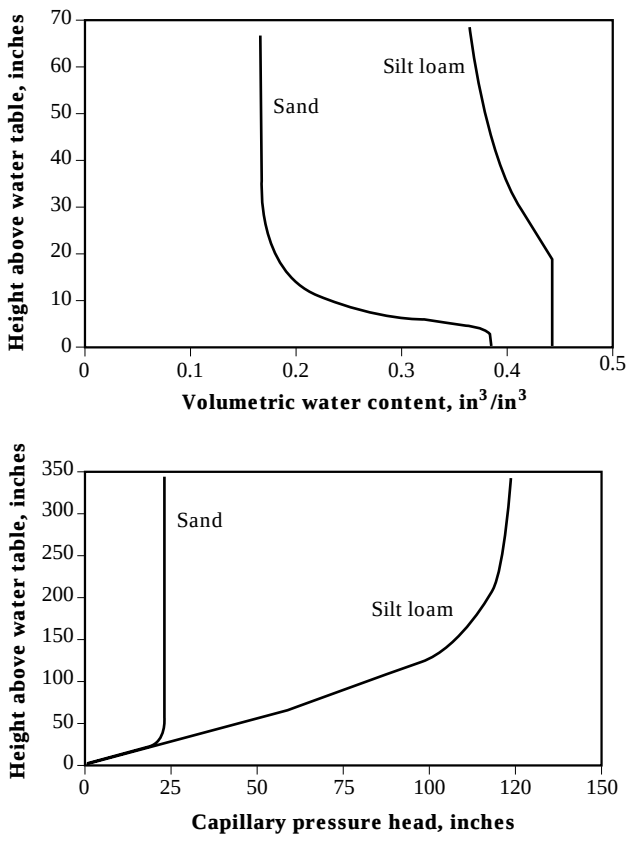
The soil properties change with soil type and the height above the water table. Figure 2–41 gives examples of the water content and capillary pressure head above a water table for two soils. At the water table, the soil is saturated (i.e., all soil pores are filled with water) and the capillary pressure head is zero. For a small distance above the water table, the soil remains saturated even though the capillary pressure head is greater than zero. The capillary pressure head where the soil becomes unsaturated is called the bubbling pressure, or the air entry pressure. Above the depth equivalent to the bubbling pressure, the soil becomes partly unsaturated (i.e., some pores are filled with air). As the depth above the water table increases, the water content of the soil decreases and the capillary pressure head increases.

The rate of decrease of water content and increase of capillary pressure head above the water table depends on the soil type. The water content of sandy soils decreases very rapidly with small changes of capillary pressure head. Thus, the water content is generally less for sands than it is for finer textured soil at equal distance above the water table (fig. 2–41).

The rate of upward waterflow depends on the unsaturated hydraulic conductivity of the soil. When the soil is saturated, the hydraulic conductivity is highest, and as the soil is dewatered, conductivity decreases (fig. 2–40). Coarse textured soils generally have a high hydraulic conductivity when saturated. The hydraulic conductivity, however, decreases very rapidly as the water content of the soil decreases. Finer textured soils have a lower initial saturated conductivity that decreases more gradually as the soil is dewatered.

The rate of upward waterflow can either be steady (i.e., not changing with time) or unsteady (i.e., changing with time). If upward flow is assumed to be steady, the rate of upward flow can be predicted for many conditions. Transient methods are needed where the water table elevation changes quickly or where it is necessary to manage the depth of the water table. Solving for the transient rate of water contribution to the crop root zone is very complex and generally requires specialized computer programs. Unsteady solutions may be necessary for combined drainage-subirrigation systems (Skaggs 1981). The DRAINMOD program is very useful for this purpose (SCS 1983) and should be consulted if unsteady upward waterflow rates are required.

Figure 2–41 Water content and capillary pressure head for two soils that have a steady, upward flow rate of 0.1 inch per day



(b) Steady upward flow

Under many conditions steady, upward flow is sufficient for predicting water contributions to crop systems. Two methods to determine the approximate rate of upward waterflow are presented. The first method, a solution provided by Doorenbos and Pruitt (1977), should be considered as an approximation for representative soil types. Because individual conditions may differ dramatically, values estimated from this method should be used with caution and verified through experience. The second method is based on the analysis of Darcy's Law using the solutions by Anat, Duke, and Corey (1965). This method, referred to as Anat's Solution, requires additional soils data as will be discussed later in this section.

(1) Doorenbos and Pruitt's Approximation

Doorenbos and Pruitt (1977) presented a graphical solution for the rate of upward waterflow for several soil types and depths of the water table below the crop root zone (figure 2–42). For example, a sandy loam soil where the water table is 3 feet below the crop root zone could be expected to supply about 0.06 inch of water per day. If the water table is only 2 feet below the root zone, the upward flow is about 0.13 inch per day.

Results from Doorenbos and Pruitt illustrate that the upward flow rate is generally most significant for medium textured soils where the hydraulic gradient and conductivity together produce a usable rate of water supply. In fact, their results show that the upward flow rate is nearly insignificant for all but the medium textured soils. For example, the clay soils (No. 1 and 3) require that the water table be within 1.5 feet of the crop root zone to provide 0.05 inch of water per day. This shallow depth could pose aeration problems in clay soils. Likewise, sandy soils, such as No. 2 in figure 2–42, will not produce substantial amounts of upward flow except where the water table is very shallow. The need to consider upward flow is most important for medium textured soils. The results in figure 2–42 can be used as an initial approximation, but more refined estimates are possible using Anat's Solution technique.

(2) Anat's solution

Anat, Duke, and Corey (1965) developed an analytic solution for equation 2–86 under the conditions of steady upward flow from a water table. They used the Brooks and Corey (1964) method to describe soil hydraulic properties. The solution developed is given by:

$$d_w = h_b \left[\frac{LN(1+q_r)}{(\eta+1)} - \frac{q_r}{(1+q_r)} + \frac{1+\frac{1.886}{1+\eta^2}}{q_r^{\frac{1}{\eta}}} \right] \qquad [2–90]$$

where:

d_w = distance from the bottom of the root zone to the water table

q_r = relative rate of upward waterflow

η = soil property defined by equation 2–89

The relative rate of upward flow is computed as:

$$q_r = \frac{q_u}{K_o} \qquad [2–91]$$

where:

q_u = rate of upward flow

The Anat Solution can be summarized using relative depth to the water table and the relative rate of flow (fig. 2–43). The relative depth below the root zone (d_r) is given by:

$$d_r = \frac{d_w}{h_b} \qquad [2–92]$$

To use the method in figure 2–43, the relative depth should be calculated using equation 2–92. The relative rate of contribution can be determined from figure 2–43. The daily steady state contribution can then be computed solving for q_u in equation 2–91. Example 2–24 helps illustrate the solution.

Figure 2–42 Water table contribution to irrigation requirements as a function of water table depth (adapted from Doorenbos and Pruitt 1977)

Soil type	Line number
Sticky clay	1
Loamy sand	2
Clay	3
Peat	4
Clay loam	5
Sandy loam	6
Fine sandy loam	7

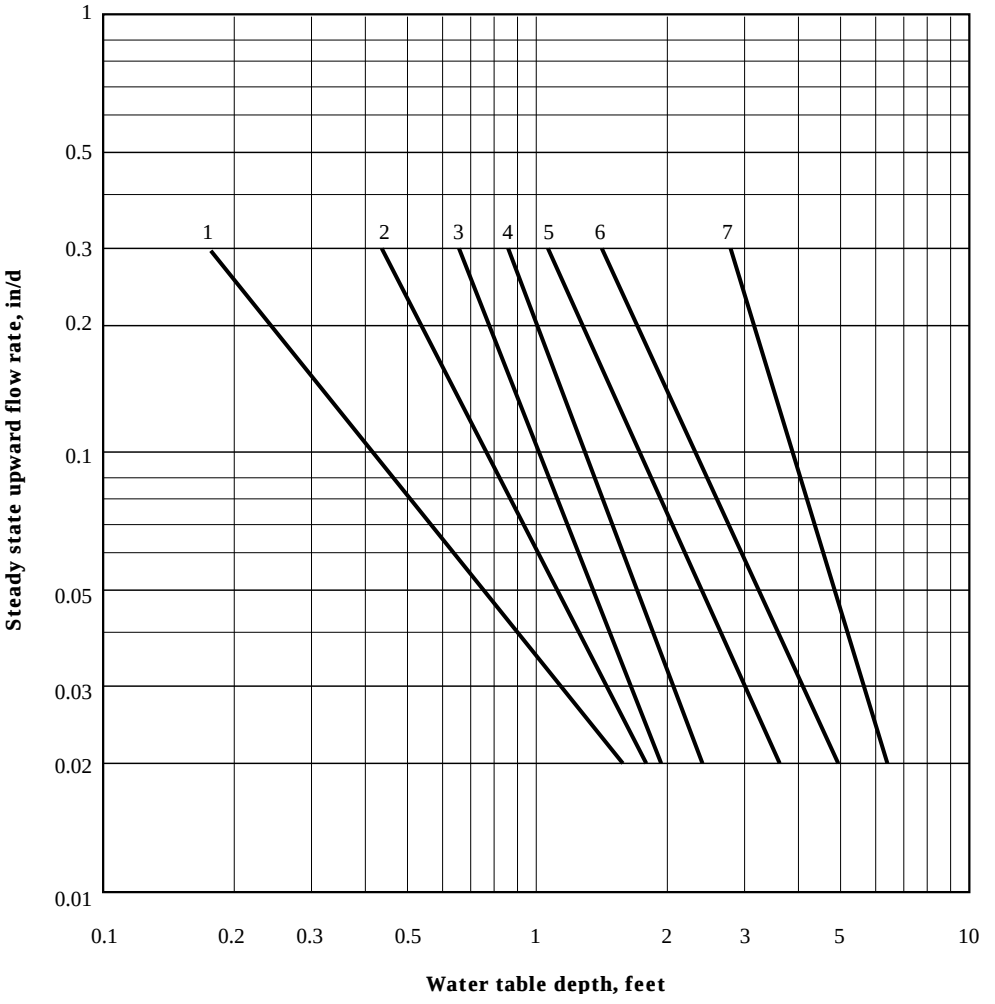
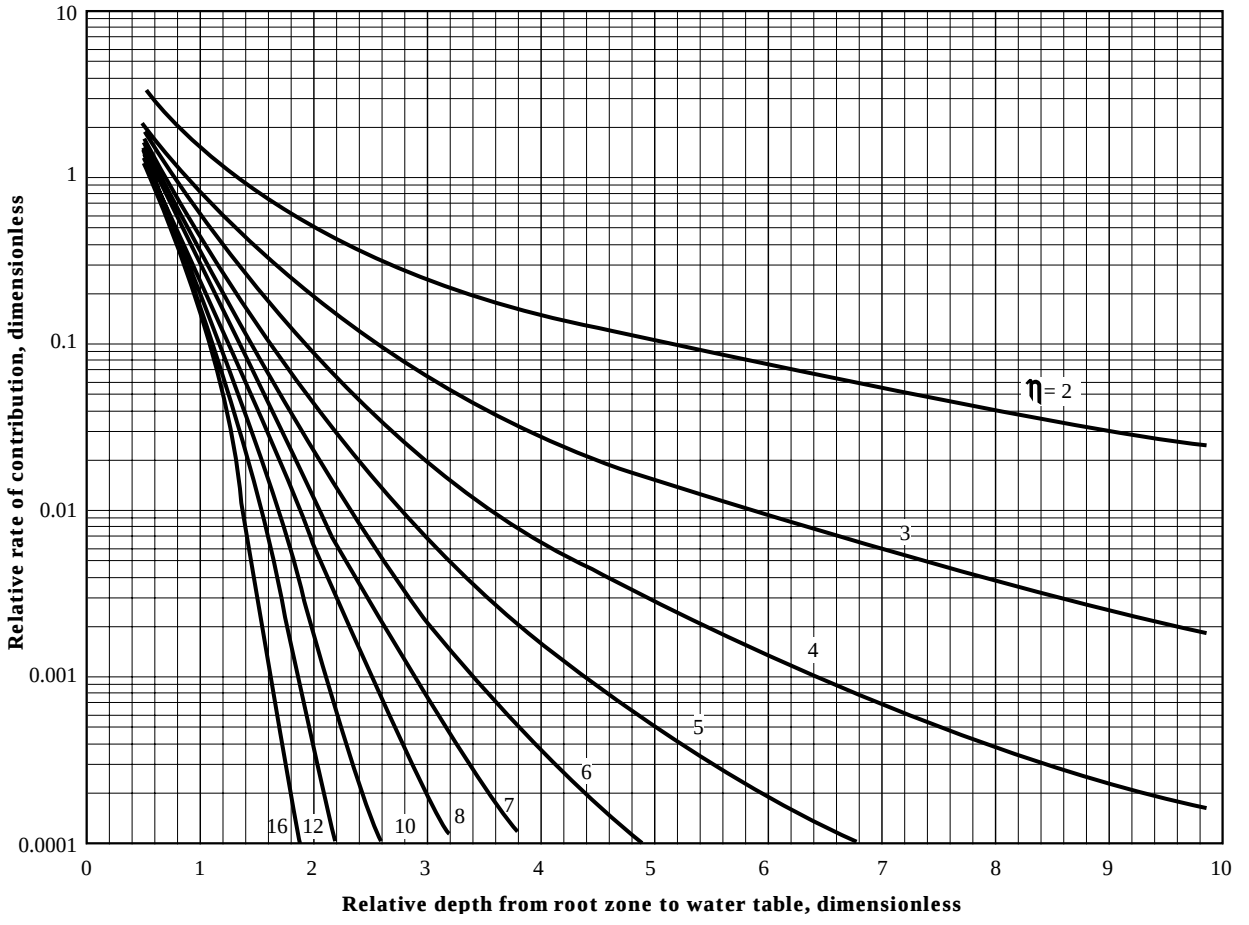


Figure 2–43 Graphical solution for the water table contribution using the Anat Solution (Anat, et al. 1965)



Example 2–24 Anat's Solution

Given: A silty clay loam soil that has a saturated hydraulic conductivity of 20 inches per day, a bubbling pressure head of 10 inches and a pore size distribution index of 1.

Required: Determine the rate of upward flow for depths to the water table of 24, 48, and 60 inches.

Solution: Compute: η using equation 2–89 $\eta = 2 + 3\lambda_p = 2 + 3(1) = 5$

relative depth (equation 2–92) $d_r = \frac{d_w}{h_b}$

Read the value for q_r from figure 2–43.

Compute: $q_u = q_r K_o$ (equation 2–91), which has the same units as K_o.

Results:

d_w (in)	d_r	q_r	q_u (in/d)
24	2.4	0.017	0.34
48	4.8	0.00056	0.011
60	6.0	0.00018	0.004

(c) Hydraulic properties of soil

The Anat Solution (Anat, et al. 1965) depends on three soil properties (K_o, h_b, and λ_p). Research has shown that these values can vary significantly for a given soil. The hydraulic data are not readily available for most soil types and require careful tests to determine. The soil properties can be determined using procedures described by Bouwer and Jackson (1974) or Shani, Hanks, Bresler, and Oliveira (1987).

The bubbling pressure and pore size distribution index are determined from moisture release data. The moisture release curve is the relationship between the volumetric water content of the soil and the capillary pressure head (figure 2–44).

The Brooks and Corey (1964) relationship for the moisture release curve given in equation 2–87 can be rewritten as:

$$S_e = \left(\frac{\theta_v - \theta_r}{\theta_s - \theta_r}\right) = \left(\frac{h_b}{h}\right)^{\lambda_p} \qquad [2–93]$$

where:
S_e = effective saturation

The effective saturation can be plotted versus the capillary pressure head as shown in figure 2–45. If the correct value of the residual soil-water content is selected, the S_e versus h data will fall on a straight line on the log-log plot. Using a trial and error procedure, the appropriate value of θ_r can be determined. Once an acceptable fit has been determined, the data can be analyzed using either a power function regression or by drawing a best fit line and determining the slope of the line. The slope of the line is equal to ($-\lambda_p$). The slope is determined by selecting two points on the line. The two points shown in figure 2–45 were at (S_e = 1.0, h = 13.5 inches) and (S_e = 0.34 and h = 200 inches).

The value of λ_p is given by:

$$\lambda_p = -\left[\frac{LN(S_{e_2}) - LN(S_{e_1})}{LN(h_2) - LN(h_1)}\right] \qquad [2–94]$$

where:
subscripts 1 and 2 = the points on the line

Figure 2–44 Diagram of the moisture release curve for a sandy clay loam soil using the method of Brooks and Corey (1965)

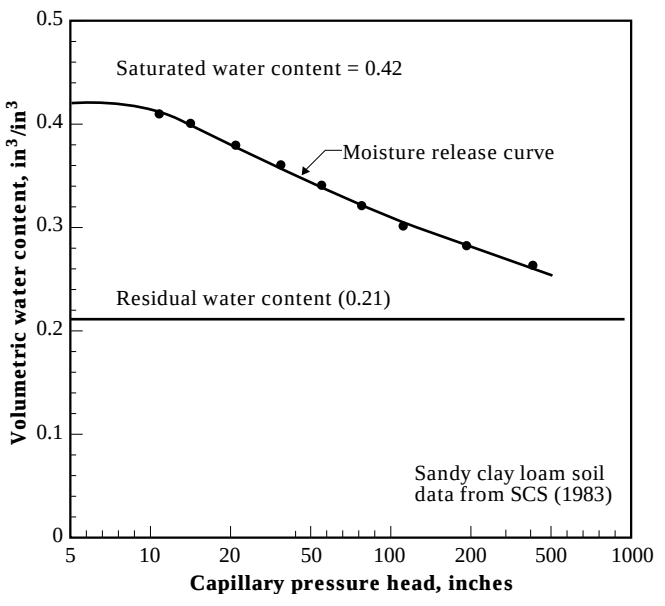
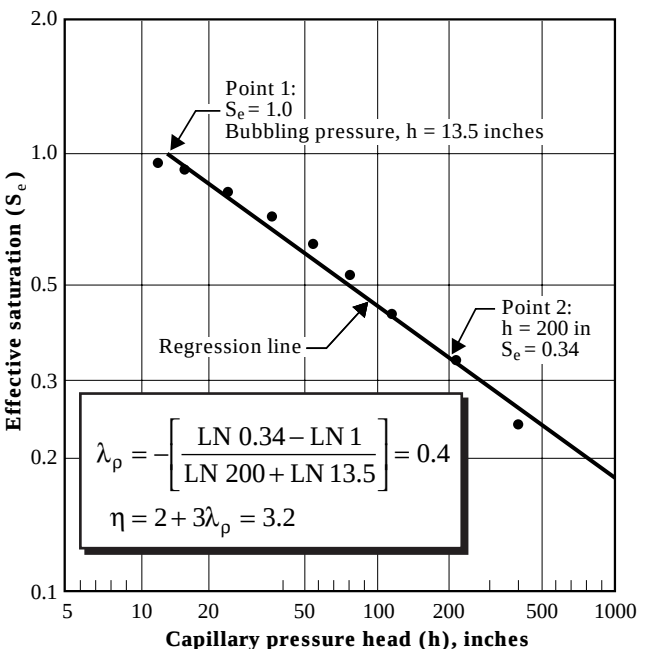


Figure 2–45 Procedure to determine the characteristic parameters for the Brooks and Corey functions



The determination of the value of λ_p for the sample data is shown in figure 2–45. The value of the η parameter is then computed using the relationship in equation 2–89.

The bubbling pressure head (h_b) can be determined when the effective saturation is equal to 1.0. From figure 2–45, the bubbling pressure head for the sample data is 13.5 inches.

The saturated hydraulic conductivity (K_o) is difficult to predict. The saturated conductivity varies for soil textures and densities, for water and soil characteristics, and for farming practices. There is widespread evidence that no-till farming substantially increases the saturated conductivity of some fine textured soils. Old root channels, wormholes, and other macropores or preferential flow channels can increase the saturated hydraulic conductivity. These large channels also provide for a very small bubbling pressure head. However, the large pores in the soil have little, if any, effect on the upward flow of water into the crop root zone. Thus, a disturbed soil sample or a sample without macropores is best used to determine the hydraulic properties for upward flow. The properties should also represent the region of the soil profile where upward flow occurs. Surface soil samples are generally not appropriate for upward flow analysis.

Experimental methods to determine the saturated conductivity have been presented by Bouwer and Jackson (1974). These methods work well for many conditions. New methods of determining hydraulic conductivity using *in situ* techniques have been reported (Shani, et al. 1987). These methods must be modified for the subsoil, but may also be very useful for field studies.

If direct measurement of the saturated conductivity is not possible, K_o can be predicted using the Brooks-Corey functions with the Childs, Collis-George integral (Brakensiek, et al. 1981). The relationship is given by:

$$K_o = 1.416 \times 10^6 \frac{\phi_e^{\,2}}{h_b^{\,2}} \frac{\lambda_p^{\,2}}{(\lambda_p + 1)(\lambda_p + 2)} \qquad [2–95]$$

where:
K_o = saturated hydraulic conductivity (in/d)
ϕ_e = effective porosity

The effective porosity ϕ_e is given by:

$$\phi_e = \phi - \theta_r \qquad [2–96]$$

where:
ϕ = soil porosity
θ_r = residual water content (fig. 2–44)

The porosity can be computed from the soil bulk density by:

$$\phi_e = 1 - \frac{\rho_b}{\rho_s \times \rho_w} \qquad [2–97]$$

where:
ρ_b = soil bulk density (lb/ft^3)
ρ_s = specific gravity of the soil solids (typically = 2.65)
ρ_w = density of water (62.4 lb/ft^3)

Using these relationships, Brakensiek, Engleman, and Rawls (1981) presented average values for the Brooks and Corey functions for various soil types (table 2–47). These values can be used as initial estimates for upward flow; however, site specific data should be obtained if possible.

Table 2–47 Average values for parameters used in the Brooks and Corey functions (adapted from Brakensiek, et al. 1981 and other sources)

Soil texture	$\phi=\theta_s$	λ_p	η	η_b (in)	K_o (in/d)
Coarse sand[1/]	0.40	1.2	5.6	5.0	1165
Loamy sand	0.40	1.00	5.0	3.8	750
Sandy loam[1/]	0.40	0.73	4.2	4.0	180
Silt loam[1/]	0.46	0.25	2.75	17.1	25
Loam	0.45	0.25	2.75	9.1	60
Sandy clay loam	0.41	0.34	3.0	10.2	47
Silty clay loam	0.47	0.16	2.5	14.5	10
Clay loam	0.48	0.26	2.8	10.7	36
Sandy clay	0.42	0.23	2.7	11.0	53
Silty clay	0.48	0.17	2.5	10.6	20
Clay	0.48	0.19	2.6	13.0	10

1/ Adjusted from data of Shani, et al. (1987).
Note: The values given in this table are typical values that depend on soil structure and other factors as well as texture. These values should be treated as estimates to be used only when better data cannot be obtained.

623.0209 Irrigation efficiencies

(a) Introduction

Irrigation efficiency is an index used to quantify the beneficial use of water diverted for irrigation purposes to a community, farm, field, or system. Overall irrigation efficiency (E_i) includes:

- Irrigation water management decisions, including timing and amount of application (irrigation scheduling)
- All losses in providing the planned irrigation water to the area irrigated

Water management decisions strongly influence E_i for surface systems, while physical site conditions and irrigation facilities control to a greater extent how uniform water can be applied in sprinkler, micro, and subsurface systems. Application uniformity is commonly measured as the irrigation system distribution uniformity (DU). How efficient channels and pipelines transport water is termed conveyance efficiency (E_c).

Micro, sprinkle, surface, and subsurface are irrigation methods. One or more irrigation system types can be used to apply water by a chosen method. For example, graded furrow, graded border, level furrow, and basin systems apply water using the surface irrigation method. The most appropriate method and system for an area depend upon physical site conditions, the crops being grown, timing and amount of water available, and management skill available. Any irrigation system can have overall irrigation efficiencies in the low to mid 90's. However, the proper irrigation method to fit the water, crop and site conditions, and a high level of management are required to accomplish such a high efficiency.

(b) Irrigation efficiency (E_i)

Irrigation efficiency is the ratio of the average depth of irrigation water beneficially used to the average depth applied, expressed as a percentage.

Irrigation efficiency represents the percentage of applied water that is potentially accessible to crop evapotranspiration, crop heating (frost control), crop cooling, crop quality control, and leaching of salts from the soil profile. The irrigation efficiency is affected by the uniformity of distribution and losses. If either the uniformity of distribution decreases or losses increase, the overall irrigation efficiency generally decreases. Irrigation efficiency is directly related to the percentage of irrigated area being under irrigated or over irrigated. Therefore, irrigation system designs that maximize uniform application as well as minimize water losses caused by improper management (often poor irrigation scheduling), evaporation, wind drift, runoff, or deep percolation produce the greatest irrigation efficiencies.

Irrigation efficiency is a function of: the irrigation method used, physical condition of the irrigation system, physical condition of the soil, plant or crop type, spacing and population, timing and amount of irrigation water applied, water management level and skill, and environmental condition at the time water is applied. The way in which these functions interact with respect to uniformity and losses determines the irrigation efficiency.

(1) Water losses during application

Water loss varies with the type of irrigation method and system, the environmental conditions under which the system is operated, and the type and condition of conveyance system. For a well designed and installed irrigation system that fits the crop, water, and site conditions, water management is the principal means available by the irrigator to ensure that losses are held to a minimum. In the absence of reliable irrigation scheduling practices, the general tendency is to over water, resulting in excess runoff and deep percolation below the root zone. However, if the dryness appearance of plants is used as an indicator for scheduling, the tendency is to under irrigate. During hot, dry days a plant whose root development depth was restricted by over irrigation early in the growing season, can show stress even though adequate moisture exists in the normal root zone. This condition usually results in over irrigation.

(2) Sprinkle irrigation method

For sprinkle irrigation, major sources of water loss include:

- Improper water management (applying water when it is not needed or in excessive amounts)
- Evaporation from droplets, the wetted canopy, and the soil surface

- Wind drift
- Runoff and deep percolation
- Leakage from conveyance system, worn nozzles, gaskets, or other equipment

Direct evaporation from droplets during irrigation is typically small except under very high evaporative conditions. Such losses are normally less than 5 percent of the total water that is applied, but increases as droplet size decreases and vapor pressure deficit increases. Losses as high as 45 percent have been measured under very low relative humidity and high temperature and wind conditions. Likewise, the longer droplets are airborne, the greater will be the water loss. Therefore, designs are preferred that minimize the height of sprinklers above the soil or canopy while still maintaining adequate uniformity and appropriate application rates.

For a given set of environmental conditions, evaporation from the wetted canopy is dependent on the type of crop, stage of growth, total leaf area, wind speed, wind direction, ambient air temperature, humidity, and duration of irrigation. Evaporation from the leaf surface of a crop canopy that covers the entire soil surface is the principal source of evaporative loss during irrigation. It amounts to as much as 25 percent of the total water loss for the day (Thompson, et al. 1988). Depending on the environmental conditions, the canopy may remain wet for 30 minutes or more after irrigation has ended. Therefore, the longer the irrigation set, the smaller the percentage of loss will be. Low Pressure In Canopy (LPIC) continuous-move laterals apply water a few inches above the soil surface low within the crop canopy, thereby eliminating the evaporation losses from the canopy. Where continuous-move LPIC sprinkler laterals apply water to less than half of the surface area and are used with appropriate soil, plant, and water management that controls water translocation, the system can be a Low Energy Precision Application (LEPA) system.

Evaporation from the soil surface varies with wind speed, temperature, and canopy development. A canopy that provides full shading for the soil surface reduces soil evaporation losses. Likewise, wind increases turbulence at the soil surface, increasing soil evaporation. The total water loss attributed to soil evaporation is typically less than evaporation from the leaf surfaces, but may become relatively significant immediately after sprinkle irrigation. Where soil loss is high, evaporation from canopy is generally low (low canopy cover). Where canopy loss is high, typically soil loss is low (shading affect from high canopy cover).

Wind drift is primarily considered a uniformity problem although it can also contribute significantly to water losses if water droplets are small or if the drift is carried outside the field. Losses are typically less than 5 percent of the applied water, but vary depending on system type, operating pressure, and orientation to the wind. Drift losses are greater where the wind direction is parallel to the lateral or line of sprinklers and the wind blows toward the outer edge of the field. In comparison, drift losses are minimized for center pivots because the angle between the wind and lateral is continually changing.

Drift is a function of droplet size, droplet shape, and wind speed. It increases rapidly for droplets that are smaller than 0.04 inch. Because wind speed increases with height above the soil surface or canopy, the greater the trajectory angle or height of the nozzle, the more drift affects uniformity of application and the potential for loss. Therefore, designs are preferred that use low sprinkler trajectories or that place the nozzle closer to the crop canopy or in the crop canopy.

Properly designed and managed sprinkle irrigation systems should not produce runoff or deep percolation. Therefore, the key to minimizing such losses is proper management. For solid-set systems, differences in application uniformity because of wind drift may result in some areas of the field receiving more than the design depth of application and other areas receiving less. Fields irrigated by center pivots are subject to runoff near the outer edge where application rates are greatest. As surface roughness and residue decrease during the growing season because of tillage, rainfall, and irrigation, soil infiltration and surface storage capacity decrease. Application rates that are acceptable early in the season can result in runoff later. In addition as water droplets impact the soil surface, infiltration rates may decrease because of surface seal formation.

For well maintained sprinkle irrigation systems, pipe leakage and drainage losses should be held to 1 percent or less. Sprinkler drainage losses can be eliminated by incorporating antidrain valves at each sprinkler. As with all irrigation systems, proper water

management and a routine maintenance program should be established and adhered to for preventing water loss and ensuring proper operation of the system.

(3) Micro irrigation method

For micro irrigation, major sources of water loss include:

- Improper water management (applying water where it is not needed or in excessive amounts)
- Evaporation from the wetted soil surface
- Runoff and deep percolation
- Leakage from conveyance system

Water is normally not discharged into the atmosphere above the crop; therefore, micro systems are not subject to drift nor to droplet and canopy evaporation except with micro sprinklers and spray nozzles. Because application rates are typically quite low, the potential for runoff is reduced compared to sprinkle irrigation. Water infiltration rates are also more constant during the growing season since surface sealing caused by puddling from droplet impact is reduced.

(4) Surface irrigation method

Major sources of water loss for surface irrigation include:

- Improper water management (applying water where it is not needed or in excessive amounts)
- Evaporation from the wetted soil and water surfaces
- Runoff and deep percolation
- Leakage from conveyance system

Surface systems are not subject to wind drift losses nor evaporation from the wetted canopy. However, runoff and deep percolation generally are greater for graded surface systems than for well managed sprinkle irrigation systems. Typically, the combined losses of deep percolation and runoff dominate to the point that evaporation loss from the soil surface is relatively minor in comparison. However, with the appropriate match of soils, crops, field gradients, and water volume, a properly designed, installed, and managed surface system can have a higher efficiency than that for sprinkle irrigation.

Because the soil is used to transport water across the field, the infiltration opportunity time varies as water is moved from the inflow end to the outflow end of the field or is stored on the soil surface generally in lower areas. Therefore, designing and managing a graded surface irrigation system for a wide variety of crops and adequately irrigating all parts of the field without over-watering another part is more difficult unless a tail water reuse system is included. With a very low gradient system, runoff can be minimized or eliminated by blocking off the end of the field or furrow, by decreasing grade or having level sections at the lower end, or by reusing the runoff water on the same or adjacent fields. Improper decreasing of tail water runoff without a reuse system can result in increased deep percolation losses and a lower distribution uniformity. Level basin, level furrow, and contour levee surface irrigation systems are relatively easy to design, install, and manage if soils are uniform and large volumes of water can be diverted or pumped onto the irrigated area.

(5) Subsurface irrigation method (subirrigation and water table control)

For subsurface irrigation systems, major sources of water loss include:

- Improper water management (primarily irrigation scheduling resulting from poor timing of water introduction, the water table being kept too high or too low)
- Evaporation from soil and water surfaces
- Deep percolation and lateral seepage

Subirrigation systems are not subject to wind drift or evaporation from wetted plant surfaces. Deep percolation losses can become significant depending on the permeability of the restricting barrier that supports the water table. Lateral seepage losses can vary greatly depending on the depth of water table in adjacent land, location of deep channels, and permeability and depth of soil strata.

Because the water table should be maintained at a nearly constant elevation, provisions should be made for irrigation water inflow or drainage and rainfall outflow. Water management involves maintaining a nearly constant water table elevation within desirable levels during periods of rainfall, no rainfall, and crop water use. Unless excess chemicals are applied to plant and soil surfaces where they can be subjected to runoff, good ground water quality can be maintained with a subsurface irrigation system. Percolating water containing soluble chemicals tend to concentrate the chemicals in the upper few inches of a free water table. As plants use water, the water table drops, leaving chemicals behind for plant use.

(c) Uniformity of application

(1) Distribution Uniformity (DU)

Distribution uniformity is the measure of the uniformity of irrigation water distribution over a field. SCS typically uses DU of low one-quarter. **DU is the ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage.**

In comparing irrigation systems, micro irrigation, level basin irrigation with uniform soils and adequate flow volume, and continuous move laterals have the greatest capability of maintaining the highest uniformity of application. Graded surface irrigation systems on nonuniform soils generally have the lowest. Depending upon the physical conditions at the site and the level of management, the reverse may also be true.

In micro irrigation, the point of water discharge is the desired point of infiltration. The volume of water available for discharge at a point downstream is independent of the depth of water infiltrated upstream. As long as the tubing is sized adequately to accommodate the system flow rate within pressure loss allowances, the discharge potential at each emission device will be similar. In addition, the time that water is available for discharge is nearly equal at all emission points along the lateral if the lateral is reasonably level.

In surface irrigation systems, flow rate downstream decreases as infiltration occurs upstream. Because water movement along the furrow or border is directly related to this available stream size, both the infiltration opportunity time and the volume of water for a given surface area decrease somewhat from the inflow to the outflow end of the field. For sprinkle irrigation systems, actual uniformity varies depending on whether the system is fixed (solid set), periodic move, or continuously moving, and the associated sprinkler nozzle discharge pattern. In the absence of wind and extreme high temperatures, properly designed, operated, maintained, and managed sprinkle systems typically have uniformity's between those of micro and graded surface systems.

The physical condition of the irrigation system may also affect the uniformity of water application. Surface systems have minimal water distribution hardware and are least affected by age or physical condition as long as soil surface smoothness is maintained. Instead, inflow rate and soil conditions, including grade uniformity, control water distribution across the field. However, this is not the case for micro or sprinkle systems. For micro irrigation, the emitter is the major cause of nonuniform water application. Because of manufacturing variations and plugging, emitters of the same size and design differ slightly from the stated discharge-pressure relationship. By using multiple emitters in the same emission area, discharge variations are minimized and reliability of applying the designed amount of water is increased. Because of their small orifices, emission devices are subject to clogging. Therefore, proper filtering of water, periodic filter back-flushing, and use of chemical treatment are required to maintain high distribution uniformity.

Sprinklers are subject to nonuniform water application because of the differences in rotation speed, changes in orifice diameter caused by wear, irregularity of trajectory angle caused by nonvertical risers, and wind effects on aerial water distribution. Wind distortion can be partly overcome by spacing sprinklers or tow paths more closely together, using sprinklers that have a lower trajectory angle, and placing sprinklers or spray nozzles closer to or within the crop canopy. If improperly designed and managed, sprinkler or spray nozzles can result in a low distribution uniformity because of crop interference. For continuously moving sprinkler systems, tower start-stop times affect uniformity, especially with sprinklers having small wetted diameters. However, such nonuniformities tend to even out over a growing season because such movements in the field are random.

Another source of nonuniformity for sprinkle and micro irrigation systems is changes in elevation along the lateral. Because micro systems normally operate at pressures much less than those for sprinkler systems, a given change in elevation has a larger relative effect on water pressure and discharge. Pressure regulators, line flow control devices, and flow control nozzles are available for both systems to reduce these variations. Pressure compensating emission devices for micro laterals can also reduce this sensitivity.

To compare the uniformity of water application between different irrigation methods and systems, methods can be developed for assigning numerical values to actual field test data. Such methods include distribution uniformity (DU) for the average low-quarter or

low-half depth and Christiansen coefficient of uniformity (CU).

For each irrigation method, DU can be used to indicate the uniformity of water application throughout the field. It is computed as: [2–98]

$$DU = 100\left(\frac{\text{Avg. low - quarter depth of water infiltrated *}}{\text{Avg. depth of water infiltrated *}}\right)$$

* For sprinkle and micro systems, use catch can measurements; for surface systems use infiltrated depth.

The average low-quarter depth of water infiltrated is the average depth of the lowest one-quarter of all measured values, each of which represent an equal area of the field. A similar definition is used for the high quarter depth and low half depth.

(2) Christiansen's coefficient of uniformity (CU)

CU is also used to evaluate application uniformity. When all areas represented by each observation are equal, CU is determined as:

$$CU = 100\left(1 - \sum_{i=1}^{n} \frac{\left|\overline{x} - x_i\right|}{n\overline{x}}\right) \qquad [2–99]$$

where:
x_i = the depth of observation i
$\overline{x}$ = mean depth for all observations
n = number of observations

When CU is greater than 70 percent, test data typically form a bell shaped curve that is normally distributed and symmetric about the mean. For such cases, CU can be approximated as: [2-100]

$$CU = 100\left(\frac{\text{Avg. low - half depth of water infiltrated *}}{\overline{x}}\right)$$

* For sprinkle and micro systems, use catch can measurements.

Using this definition, an approximate relationship between DU and CU can be written as:

$$CU = 100 - 0.63(100 - DU) \qquad [2\text{-}101]$$

Similarly, this can be solved for DU as:

$$DU = 100 - 1.59(100 - CU) \qquad [2\text{-}102]$$

(d) Application efficiency (E_a)

Application efficiency is the ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied, expressed as a percentage.

Application Efficiency Low Quarter (AELQ) is the ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage. This term is most often used in defining management effectiveness.

The greatest irrigation water loss generally results from applying too much water too soon (improper irrigation scheduling). Deficit irrigation of a significant part, or all, of the irrigated area is an exception. Other water losses include evaporation from soil and leaf surfaces, runoff, percolation below the plant root zone, and wind drift. In all cases irrigation water management has a large influence on the net amount of water available for beneficial use. **Application efficiency is primarily affected by operator irrigation water management decisions.** An adequately designed and installed system can be badly mismanaged.

Evaporation losses vary with the irrigation method, system used, and system operation. It can occur directly from the wetted soil or water surface, wetted plant canopy, and droplets discharged from sprinkler nozzles. Evaporation from the soil surface relative to other losses decreases as the depth of application increases. Surface, subsurface, and micro systems (except micro sprinklers and sprays) are subject only to evaporation at the soil surface since the canopy is not wetted during irrigation. As the crop canopy develops and the soil is shaded, soil evaporation losses are further reduced. Evaporation from sprinkle irrigation tends to be greater than that from surface and micro systems because of the increased surface area wetted as well as that water may be discharged directly into the atmosphere above the crop canopy. As wind speed and vapor pressure deficit increase and droplet size decreases, droplet evaporation increases.

Runoff is a function of soil surface slope and storage, the infiltration rate of the soil, and the application rate of the irrigation system. Properly designed micro and

sprinkler systems should have no runoff if correctly designed, installed, and managed. Water management is important with all irrigation systems. This is especially true for sprinkler systems because the impact of droplets on the soil surface can reduce surface storage and can produce a surface seal that reduces infiltration during subsequent irrigations.

To be adequately and fully irrigated, all graded surface irrigation systems must have some runoff unless the end of the field is severely underwatered, level field sections are provided at the outflow end, or the ends are blocked on low gradient fields. With nearly level surface irrigation systems, small dikes across the end can be used to increase irrigation uniformity. Blocked ends are most effective when opportunity time is increased on the lower third to fourth of the field. Runoff loss from the field can also be reduced if tail water is collected for reuse on the same or adjacent fields.

Deep percolation occurs where the infiltrated volume of water exceeds the volume needed to bring the soil-water content in the plant root zone to field capacity. Properly designed and managed irrigation systems that are installed on suitable sites can have very little or no water lost to deep percolation. Unless the upper fourth of the field is chosen for the design application depth, some deep percolation always occurs where graded surface irrigation is used. This is necessary to ensure sufficient stream size and infiltration opportunity time at the outflow end of the field for filling the root zone to field capacity or to some planned lesser level.

Cutback, tail water reuse, surge, or cablegation techniques can be used to minimize deep percolation losses. Often irrigation stream size is decreased to reduce or eliminate tail water runoff at the expense of increasing deep percolation and irrigation nonuniformity. Runoff and deep percolation should be managed because they largely affect efficiency and are the primary transport mechanisms for off-site surface and ground water pollution.

The term most often used to define management effectiveness is application efficiency (E_a). However, because application efficiency is a function of water losses, a high value does not necessarily mean an effective and uniform irrigation. For example, runoff and deep percolation can be eliminated by severely underwatering, but an E_a near 100 percent can result. (E_a cannot exceed 100 percent.) If insufficient water is stored in the root zone in most of the irrigated area to meet the crop water requirements, crop performance (yield or biomass) will be reduced. Therefore, a more complete definition of an effective irrigation should include the concepts of adequacy and uniformity of application. (See equations below.)

$$E_a = 100\left(\frac{\text{Average depth of irrigation water stored in the root}}{\text{Average depth of irrigation water applied}}\right)$$

$$\text{AELQ} = 100\left(\frac{\text{Avg. depth of irrig. water stored in the low quarter root zone}}{\text{Avg. depth of irrigation water applied}}\right)$$

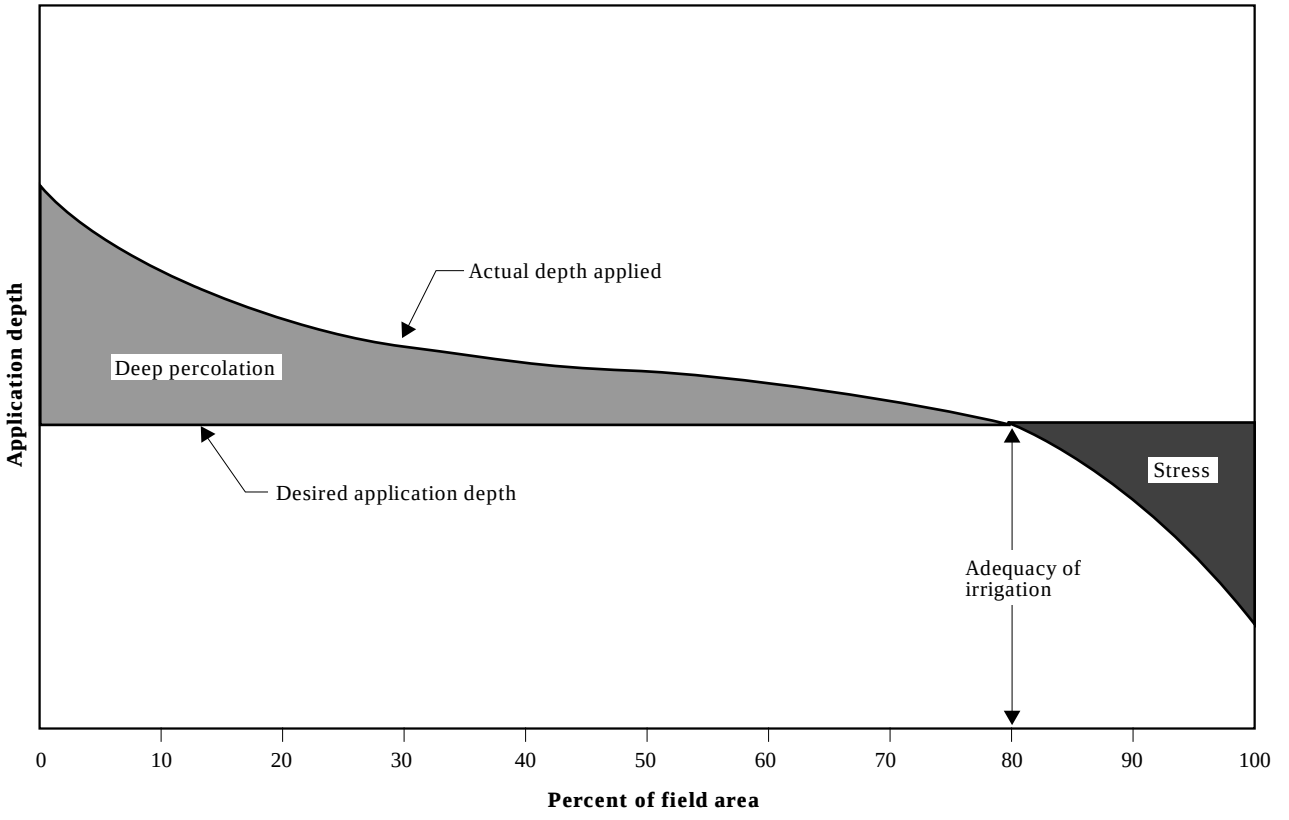
(e) Irrigation adequacy

(1) Adequacy of irrigation

Adequacy of irrigation is the percentage of the field that receives the desired amount of water. In arid and semi-arid regions where the probability of sufficient rainfall is low, each irrigation typically fills the soil profile to field capacity or to some planned lesser level. In sub-humid and humid regions, this may be less than field capacity to provide storage for rainfall that may occur between irrigations. The choice of how much water to apply may also be a function of the sensitivity of the crop to water stress, its market value, and water supply.

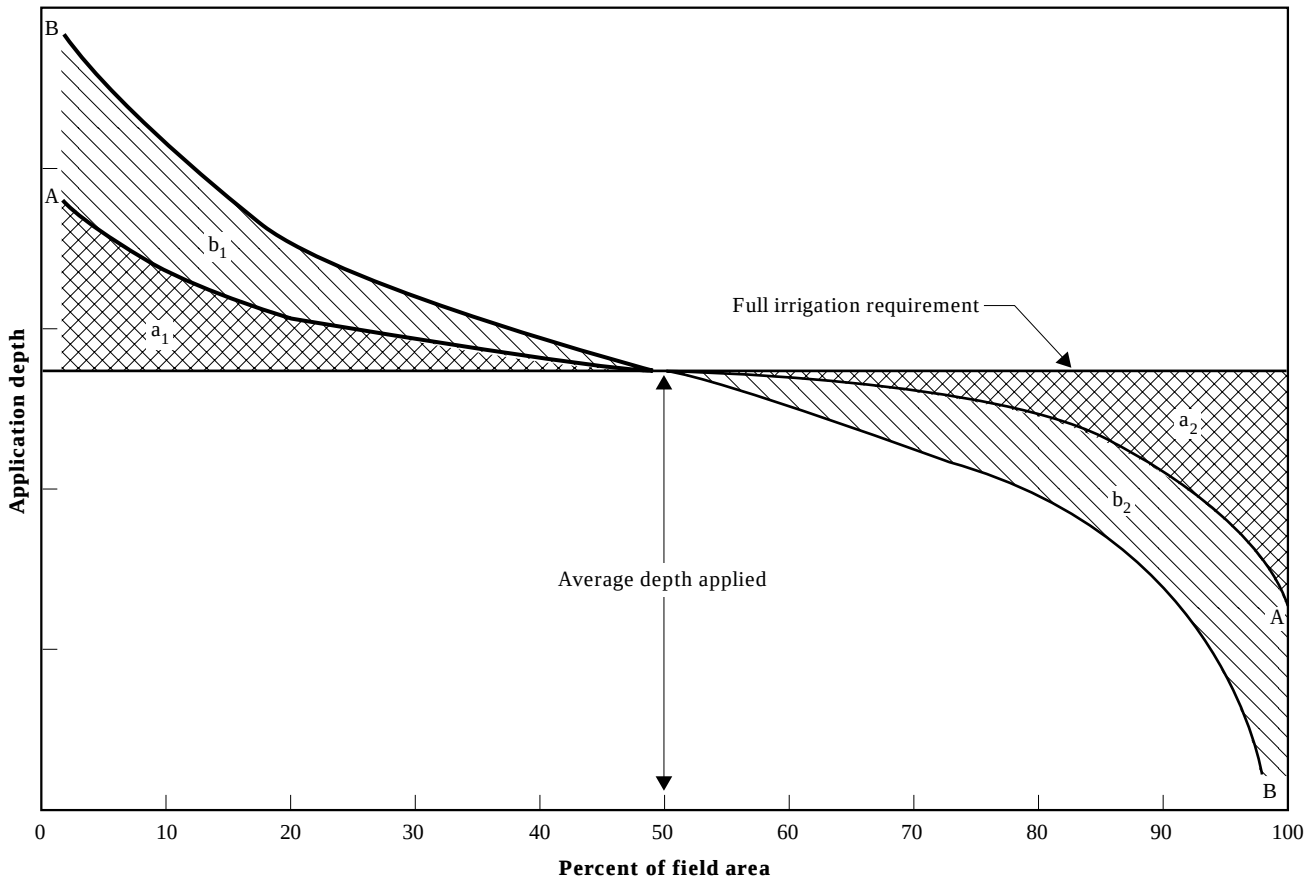
Adequacy of irrigation can most easily be evaluated by plotting a depth of application distribution as shown in figure 2–46. The curve is developed by grouping field measurements of application depth in descending order, accounting for the field area that each measurement represents. The point where the curve intersects the line for desired application depth indicates the percentage of the field that is being adequately irrigated. Note that the distribution gives the amount of water applied (received by each part of the field and can be used to calculate DU, the area under irrigated, and the area over irrigated). Deep percolation moves chemicals below the root zone and can contribute to ground water pollution. Both under and over irrigation can result in crop yield and quality reduction.

Figure 2–46 Distribution of field application depth indicating adequacy of irrigation



The relationship DU and E_a is demonstrated in figure 2–47. Here, two irrigation systems (A and B) having the same adequacy, but different uniformity's and E_a are shown for the same field. The application depth for each system is equal to the area under the curve for full irrigation (i.e., field capacity). Therefore, if uniformity of application (DU or CU) was 100 percent, both curves would fall exactly along the line for full irrigation. Note that since curve A is flatter, it has the better uniformity. The amount of over and under irrigation for system A is represented by the area a_1 and a_2, respectively, and for system B as a_1+b_1 and a_2+b_2, respectively. Because over irrigation (potential for runoff and deep percolation) is greater for system B, that system has a lower E_a than system A. Therefore, for irrigation systems designed to apply water to field capacity, improving application uniformity also improves the E_a. However, this is not be true for systems that under or over water the entire field because the total amount of water loss remains unchanged.

Figure 2–47 Distribution for two irrigation systems having equal adequacy but different uniformity and application efficiency



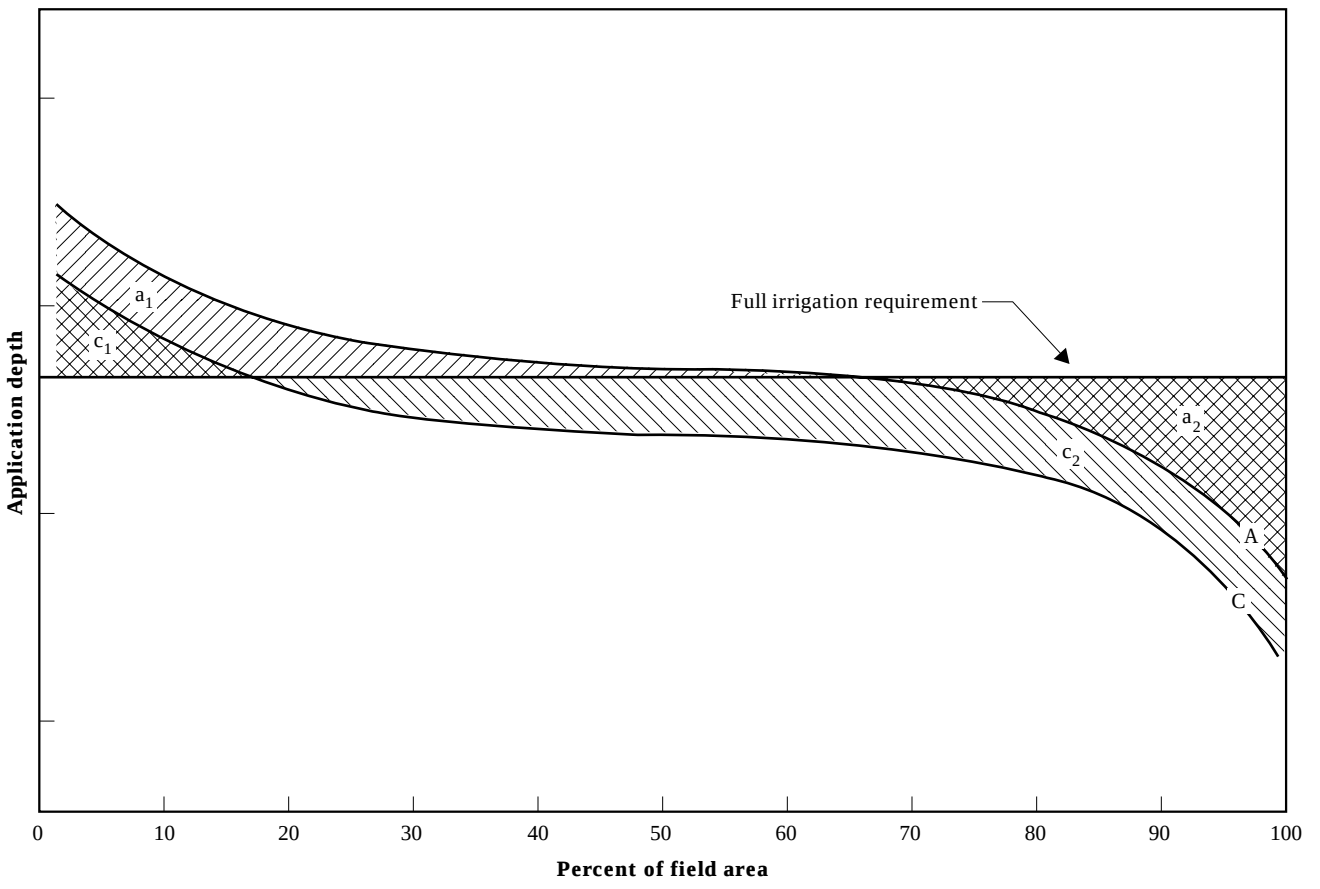
The relationship of adequacy and E_a is shown in figure 2–48. Here, a third system (C) is used that has the same uniformity as system A. System C has a lower adequacy and therefore is not applying sufficient water for the root zone to be filled to field capacity. The amount of over and under irrigation for system A is represented by a_1+c_1 and a_2, respectively. For system C, this is c_1 and a_2+c_2, respectively. Because system A has the greater percentage of over irrigation (potential runoff and deep percolation), system C now has the greater E_a. However, improving E_a by decreasing application depth below full irrigation does not necessarily result in a more effective irrigation. Depending on the market value, water-stress sensitivity of the crop, and price of energy and water, this may or may not improve net income.

(2) Sprinkler systems

A concept that combines a measure of uniformity and E_a and provides for adequacy considerations is the Application Efficiency of the Low Quarter (AELQ) or the Application Efficiency of the Low Half (AELH).

AELQ is the ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage. AELH is the ratio of the average of the low one-half of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage. AELQ and AELH can be measured by conducting field tests of existing systems.

Figure 2–48 Distribution for two irrigation systems having equal uniformity but different adequacy and application efficiency



Application efficiencies are termed to be potential when the amount of water applied equals the design amount needed in all areas. This condition seldom exists because of the many variables the irrigation decisionmaker must consider. These variables include under or over estimating soil water needed to refill the plant root zone to field capacity, nonuniform irrigation system application, nonuniform soil characteristics, and nonuniform plant water use.

For sprinkle irrigation systems, potential AELQ can be estimated for design and planning purposes by:

$$\text{potential AELQ} = DU \times R_e \qquad (2\text{–}103)$$

where:
AELQ = application efficiency of the low-quarter (%)
DU = distribution uniformity (%)
R_e = effective part of the applied water that reaches the soil surface

R_e is a function of wind drift and evaporation loss and normally varies between 0.8 and 1.0.

To include the consideration of adequacy for medium to high value crops, the gross depth of irrigation water to be applied can be determined by dividing the Soil Moisture Deficit (SMD) by AELQ for the system. This will result in about 10 percent of the total field area receiving less water than needed to reach field capacity with the rest of the field reaching or exceeding field capacity. This is acceptable for medium to high-valued crops, but may be impractical for lower valued crops or irrigation in a water-quality sensitive area. With lower value crops, an application efficiency based on the average low-half of applied depth may be more practical.

For design purposes, the ratio of the average low-half of irrigation water available to the crops to the average depth of water applied to the field (AELH) can be estimated by:

$$\text{potential AELH} = CU \times R_e \qquad [2\text{–}104]$$

where:
AELH = application of efficiency of the low-half (%)
CU = Christiansen coefficient of uniformity

To include the consideration of adequacy for low to medium value crops, the gross depth of irrigation water to be applied can be determined by dividing the SMD by AELH. This will result in about 20 percent of the total field area not reaching field capacity after irrigation with the rest at or above field capacity.

A typical range of AELQ and AELH values for various types of sprinkle irrigation systems is shown in table 2–48. These values are based on the assumptions of a fully developed crop canopy and a properly designed and managed sprinkler system that is well maintained. Values will be lower where proper water and system management are not followed.

For sprinkler systems having a CU of more than 60 percent, sprinkle water application generally is distributed normally. Using this fact, Walker (1979) has shown that system application efficiencies can be determined based on the fractional area of the field that is under irrigated (A_u) and the coefficient of uniformity (CU) of water distribution.

The relationship between application efficiency, E_a, and CU is shown in figure 2–49. E_a can be solved explicitly using the following relationship:

[2-105]

$$E_a = 100\left[1-\left(1.25-0.0125\,CU\right)\left(3.634-1.123\,A_u^{0.3}+0.003\,A_u^{1.233}\right)\right]$$

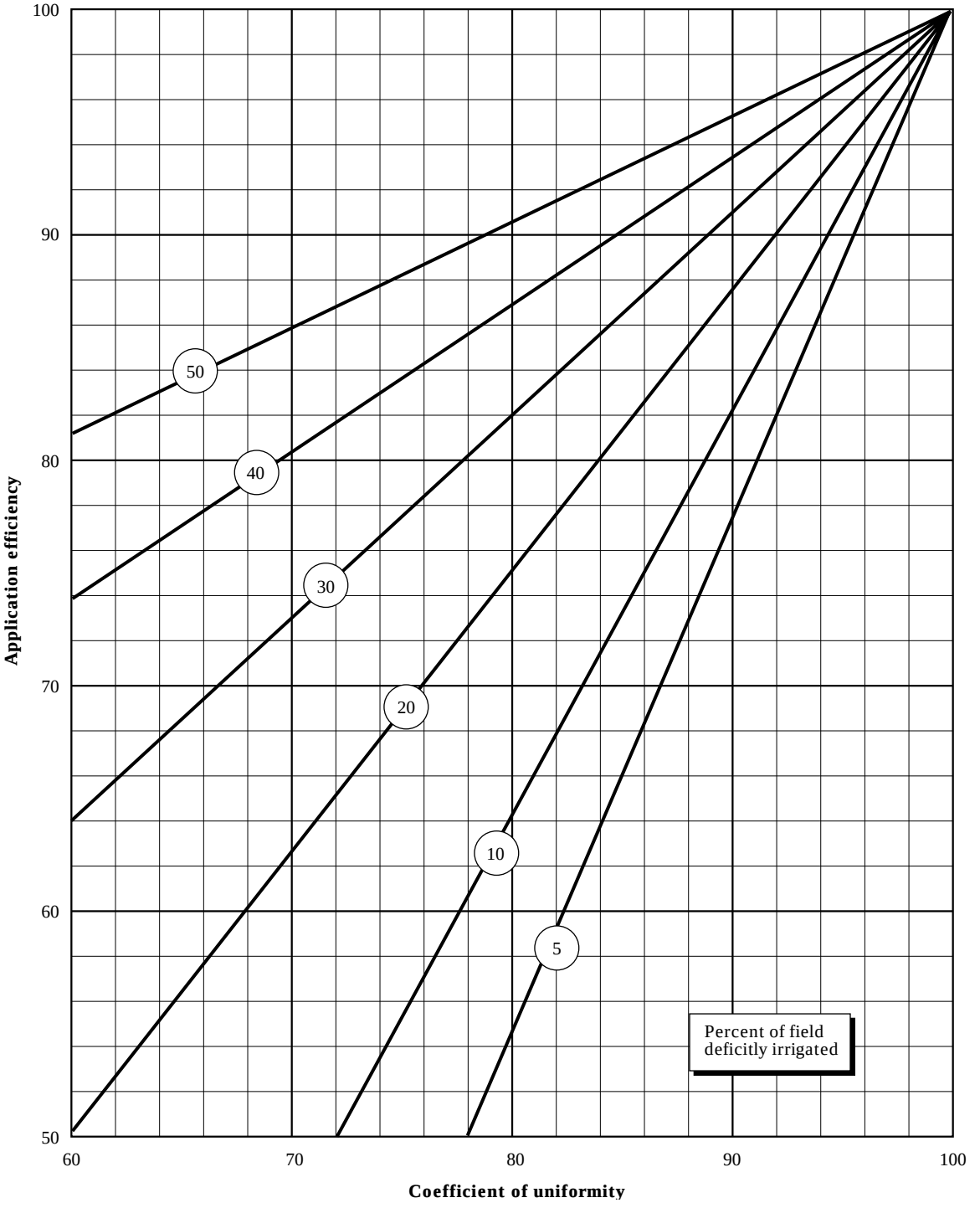
where:
E_a = application efficiency (%)
A_u = fraction of the field that is deficitly irrigated
CU = coefficient of uniformity

This equation assumes that runoff and in-air losses are negligible.

Table 2–48 Probable application efficiencies of the low-quarter (AELQ) and the low-half (AELH) for various types of sprinkler systems (adapted from the USDA-SCS National Engineering Handbook, Sprinkler irrigation)

System type	AELQ (%)	AELH (%)
Periodic move lateral	60 – 75	70 – 85
Gun or boom sprinklers	50 – 60	60 – 75
Fixed lateral	60 – 85	70 – 88
Traveling sprinklers	55 – 67	65 – 77
Center pivot	75 – 85	80 – 88
Lateral-move	80 – 87	85 – 90

Figure 2–49 Application efficiency as related to the coefficient of uniformity and the percent of the area that is deficitly irrigated



(3) Micro systems

The relationship shown in figure 2–49 can be applied equally well to micro systems (Howell, et al. 1986). Additional information is available from the USDA-SCS National Engineering Handbook, Trickle Irrigation.

(4) Surface systems, graded furrow

Typical values of water application efficiencies for furrow irrigation systems are shown in tables 2–49 and 2–50. These values are for no runoff reuse and for 75 percent runoff reuse respectively. Efficiency values represent the maximum or partial application efficiency that could be typically attained, based on the SCS method of furrow irrigation design and a net depth of application for the end of the furrow. For example, a furrow length was assumed to be 900 feet and furrow spacing 2.5 feet, with a roughness coefficient of 0.04 and constant stream inflow. Maximum set time was 12 hours, and maximum flow rate was based on the maximum nonerosive stream size (i.e., Q_{max}, gpm = 10/slope in percent) for low erosion resistant soils.

Blanks in tables 2–49 and 2–50 represent situations where it was not possible to achieve these conditions. These were mostly soils in SCS furrow intake families of 0.5 or less. Excessive set time is the primary cause. These conditions could not be met for soils in the 0.1 intake family that have slope of more than 0.1 percent at net application, F_n, depth values greater than 2 inches. Therefore, graded furrow irrigation is not recommended on these soils. For intake families greater than 0.5, as slope increases, the stream size required to provide sufficient flow at the end of the furrow typically exceeds the maximum nonerosive stream size. For these conditions, either a shorter furrow length should be used or other irrigation systems considered.

Table 2–49 Example water application efficiencies (%) for furrow irrigation by slope and intake family **assuming no reuse of runoff** 1/

Furrow length = 900 ft Furrow spacing = 2.5 ft Manning's *n* = 0.04

Uniform slope (S_o)	Furrow Intake family 0.3			0.5			0.7			1.0			1.5		
	F_n 2/ (in)														
(ft/ft)	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
level 3/	80	85	85	70	80	80	65	75	80	60	70	75	50	65	70
0.0010												50			50
0.0020					50			50	55		55	60		55	60
0.0030				50	55		50	60	60	50	65	70		65	70
0.0040	50			55	60		55	65		55	70	75		70	75
0.0050	55			60	65		60	70		60	75	80			
0.0075	60			70			70	80			80	85			
0.0100	70			75			75	85							
0.0150	80			85	90				90						
0.0200	85				90										
0.0250	90														
0.0300	90														

1/ Design efficiencies below 70 percent generally are not recommended.
2/ F_n is the desired net depth of application.
3/ Results for level fields assume no runoff (i.e., diked ends).

The data in tables 2–49 and 2–50 provide initial estimates of application efficiencies for furrow systems and were derived using standard USDA-SCS methods (NEH, Furrow Irrigation, 2nd ed.). Many conditions are not represented by these tables. They include more or less erosive soils with associated maximum stream sizes, different set times, different furrow lengths or spacing, cracking soils, nearly level fields, and blocked end furrows. More advanced surface irrigation simulation methods, such as kinematic wave zero-inertia, should be considered. Obviously, consideration of all these factors is beyond the scope of this chapter.

Values in tables 2–49 and 2–50 represent a range of values that are appropriate for initial design and planning for the selected site condition. The final design requires use of standard USDA-SCS methods for furrow irrigation.

Example 2–25 illustrates the use of tables 2–49 and 2–50. A more detailed analysis, including equations and recommended flow rates, is in the USDA-SCS National Engineering Handbook chapter on Furrow Irrigation.

Table 2–50 Example water application efficiencies (%) for furrow irrigation by slope and intake family **assuming a runoff reuse efficiency of 75 percent** 1/

Furrow length = 900 ft Furrow spacing = 2.5 ft Manning's n = 0.04

Uniform slope (S_o)	Furrow Intake family														
	0.3			0.5			0.7			1.0			1.5		
	F_n 2/ (in)														
(ft/ft)	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
level 3/	80	85	85	70	80	80	65	75	80	60	70	75	50	65	70
0.0010	55	60		55	65	65	55	65	65	50	60	65		60	65
0.0020	65	60		60	70	70	60	70	70	55	65	70	50	65	70
0.0030	65	60		65	70	70	65	70	75	60	70	75		65	75
0.0040	70	55		70	75	70	65	75	80	60	70	75		70	75
0.0050	70	55		70	75	70	70	75	80	65	75	80			
0.0075	75			75	80		70	80	85		80	85			
0.0100	75			75	85		75	85	90						
0.0150	80			85	90				90						
0.0200	85				90										
0.0250	90														
0.0300	90														

1/ Design efficiencies below 70 percent generally are not recommended.
2/ F_n is the desired net depth of application.
3/ Results for level fields assume no runoff (i.e., diked ends).

Example 2–25 Determining the gross application for graded furrow irrigation

Given:

Intake family (I_f)	0.5
Net depth of application (F_n)	4 in
Furrow slope (S_o)	0.0040 ft/ft
Roughness coefficient (*n*)	0.04
Furrow length	900 ft

Determine: Gross application depth required.

Solution: Using table 2–49, find the column heading for the soil intake family of 0.5 and locate the column for F_n = 4 inches. Move downward until you intersect the row having a value of S_o = 0.0040 ft/ft in the left most column and read an E_a = 60 percent. The gross application depth required is:

$$F_g = 100\left(\frac{F_n}{E_a\,\%}\right) = 100\left(\frac{4\text{ in}}{60\%}\right) = 6.7\text{ in}$$

Therefore to ensure that the design net application depth of 4 inches was applied at all locations in the furrow, a gross depth of 6.7 inches must be applied.

If runoff water was reused with an efficiency of 75 percent (i.e., 75% of all runoff was applied back to the same or an adjacent field), then using table 2–50 and the same procedure as above, E_a would equal 75 percent.

$$F_g = 100\left(\frac{F_n}{E_a\,\%}\right) = 100\left(\frac{4\text{ in}}{75\%}\right) = 5.3\text{ in}$$

Therefore to ensure that the design net application depth of 4 inches was applied at all locations in the furrow, a gross depth of 5.3 inches must be applied.

(5) Surface systems, graded border

Suggested values of water application efficiencies for graded border irrigation systems as taken from the USDA-SCS National Engineering Handbook chapter on Border Irrigation are shown in table 2–51. These values assume gently sloping, well-leveled fields; adequate facilities for water control and distribution; and proper management. As shown in the table, field application efficiencies are greatest for soils that have a moderate intake rate. Also, as field slope decreases application efficiency increases. Erosion can become a problem where the slope is more than 4 percent.

Border irrigation is not recommended where slope is more than 6 percent. Example 2–26 illustrates the use of table 2–51. As with furrow irrigation, table 2–51 is for planning and initial design. A more detailed analysis, including design equations and recommended flow rates, is in the USDA-SCS National Engineering Handbook chapter on Border Irrigation.

Example 2–26 Use of the application efficiency table (table 2–51) for graded border irrigation

Consider:

Intake family (I_f)	1.0
Net depth of application	4 inches
Field slope (S_o)	0.0010 ft/ft

Determine: Gross application depth required.

Solution: Using table 2–51, find the column corresponding to an intake family of 1.0 and net application depth of 4 inches. Move down this column until you intersect the row for S_o of 0.0010 ft/ft and read an efficiency of 75 percent. The gross application depth required is:

$$F_g = 100\left(\frac{F_n}{E_a\,\%}\right) = 100\left(\frac{4\text{ in}}{75\%}\right) = 5.3\text{ in}$$

Therefore to ensure that the design net application depth of 4 inches was applied at all locations in the field, a gross depth of 5.3 inches must be applied.

Table 2–51 Suggested application efficiency for graded border irrigation systems

Field slope, S_o (ft/ft)	Border intake family 0.3				0.5					1.0					1.5					2.0					3.0				4.0			
	Net depth of irrigation (F_n), in																															
	1	2	3	4	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	2	3	4
0.0005	65	65	70	70	65	65	70	70	70	75	75	80	80	80	75	75	80	80	80	75	75	80	80	80	65	70	70	70	65	70	70	70
0.0010	60	60	65	65	65	65	70	70	70	70	70	75	75	75	75	75	80	80	80	75	75	80	80	80	65	70	70	70	65	70	70	70
0.0020	60	60	55	50	65	65	70	70	70	65	65	70	70	70	70	70	75	75	75	70	70	75	75	75	65	70	70	70	65	70	70	70
0.0030	55	55	50		60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	65	70	70	70	65	70	70	70	65	70	70	70
0.0040	55	50			60	60	65	60	55	60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	70	70	70	60	65	65	65
0.0050	50				60	60	60	55	50	60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	70	70	70	60	65	65	65
0.0075					55	55	50			60	60	65	65	65	60	60	65	65	65	65	65	70	70	70	65	70	70	70	60	65	65	65
0.0100					55	55				60	60	65	65	65	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
0.0150					55					55	55	60	60	60	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
0.0200					50					55	55	60	55	50	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
0.0250										55	55	55	50		60	60	65	65	65	60	60	65	65	65	60	65	65	65		60	60	60
0.0300										55	55	50			55	55	60	60	60	55	55	60	60	60	55	60	60	60		60	60	60
0.0400										50	50				55	55	60	60	55		55	60	60	60		60	60	60				
0.0500															55	55	60	55	50		55	60	60	60								
0.0600															50	50	55	50				55	55	55								

(6) Surface systems, level furrow, border, or basins

In level furrow, border, or basin irrigation, fields are divided into level, generally rectangular areas surrounded by dikes or ridges. During irrigation, water is turned in at one or more points as needed until the gross volume of water required to infiltrate the desired net depth of application at all points in the field has been discharged. Because there is no runoff, application efficiencies are normally quite high as long as deep percolation losses are minimized. Level furrow, border, or basin systems are the easiest irrigation systems to manage.

Level furrow, border, or basin irrigation works best with soils that have a low to moderate intake rate. Level systems can be adapted to soils that have a high intake rate, but the length of run must be shortened to prevent excessive deep percolation near the inflow points. Applying large irrigation depths with these systems on soils that have a very low infiltration rate is not advised. The soil surface may be inundated for a considerable period to infiltrate the large water application, which can lead to poor soil aeration or crop scalding, stunting, or death.

Table 2–52 Design application efficiency of level systems as function of the advance ratio AR, where AR = advance time/net opportunity time = T_t/T_n 1/

Design application efficiency E_a = %	Advance ratio AR = T_t/T_n
95	0.16
90	0.28
85	0.40
80	0.58
75	0.80
70	1.08
65	1.45
60	1.90
55	2.45
50	3.20

1/ A design application efficiency below 70 percent is not recommended.

The design application efficiency for level systems generally is recommended to be at least 80 percent. To ensure this, flow rates should be large enough to completely cover the area within 60 to 75 percent of the time required for the design application depth to infiltrate (table 2–52). A design application efficiency of 70 percent is only appropriate for clean water and soils that have good internal drainage so that excess water that can cause crop damage drains from the root zone.

Experience may show, with some soils or crops, advance time can be decreased by having a very low in-row gradient within the level area (and with no side fall). By SCS definition, level furrow, border, and basin irrigation systems can have a total fall for the length of run of up to one-half the net depth of irrigation, F_n. For example, a 1,300 foot length of run can have up to 2 inches total fall (S_o = 0.000128 ft/ft) if $F_n \geq 4.0$ in.

(7) Subsurface systems, water table control, subirrigation

With subsurface irrigation, plants use water from a shallow water table that either occurs because of the natural site conditions or is developed and maintained by introduction of water. Upon soil profile drying by evaporation from the soil surface or transpiration from plants, a water potential gradient develops that allows water to move upward in the soil profile and be taken up by plant roots. See part 623.0208, Water table contribution.

The water table must be maintained at a depth below the soil surface so that upward flux of water in the soil profile is maintained. Before the water table reaches a critical elevation, water is added by use of properly spaced open channels or buried conduits. These open channels and buried conduits act as a drainage system and as an irrigation water distribution system. Overall, less irrigation water is needed as more effective use is made of rainfall and fewer losses can occur. Adequate surface drainage and subsurface drainage for water table control are essential to obtain good irrigation efficiencies. Most efficient water use is obtained where the water table is managed at the deepest depths that will provide moisture to the plant roots because evaporation from soil surface decreases as the depth of water table increases.

Equations 2–1, 2–8, 2–83, and 2–106 provide the process for evaluating the water balance for the desired period of evaluation. The most difficult item to determine in the water balance equations 2–1 and 2–8 is deep percolation below the crop root zone, which would also include lateral movement losses. With proper design and installation on suitable sites, a subsurface irrigation system can have quite a high overall irrigation efficiency. Proper operation and management are essential. Because of the wide variability of site conditions and systems, reference to local irrigation and drainage guides is suggested for design and operation of subsurface irrigation systems.

(f) Conveyance efficiency (E_c)

Conveyance efficiency (E_c) is the ratio of the water delivered to the total water diverted or pumped into an open channel or pipeline at the upstream end, expressed as a percentage.

In the Western States, an estimated one-third to one-half of the water diverted for irrigation is lost between the source and the point of use. A large percentage of this water is lost because of leakage and operational spills in conveyance systems. These losses can occur both on the farm and in group owned facilities. Conveyance losses result primarily from

- Seepage from ditches, canals, and pipelines
- Leakage through and around headgates and other structures
- Operational spills
- Consumptive use by phreatophytes

Some loss in conveyance is unavoidable. However, losses may be greatly reduced by lining earth ditches and canals or converting to pipelines; by repairing and maintaining canals and pipelines, headgates, and other structures; and by destroying or removing undesirable phreatophytes near or in the delivery system. Conveyance losses can serve as local ground water recharge or for maintaining artificial wetlands. Reduction of conveyance losses should be weighted against the affects of cutting off the water source to those other uses. Mitigation may be required.

Significant losses of water can also occur if the delivery system is not properly operated and undesirable spills occur in the system. The conveyance loss should be known to design, operate, and renovate delivery systems. On existing systems, it may be necessary to determine the actual conveyance loss and location.

The primary water loss in many conveyance or delivery systems is less than optimum water management. Up to 50 percent of water carried may be *management* or *pass through* water. Often this water is used or wasted on fields near the lower end of the delivery system, causing over irrigation. Water required for management can be reduced significantly by using automated water, electric, or pneumatic self actuating control valves and headgates. Discharge rates are controlled by either upstream or downstream sensors.

Losses of water during operation of the delivery system can occur in several ways that vary from project to project. Some water may be lost when closing or opening control elements. Other losses occur if the irrigator does not use all the water for all the time delivered by the supplier and allows the surplus to pass through. An example of this loss becoming significant occurs when a general rain occurs in the project area after water has been released upstream for use. Often an irrigation water supplier carries unaccounted for management water. On large projects with normal management, regulatory losses can vary from 5 to 50 percent of the diversion. These losses can generally be maintained below 10 percent on carefully managed, manually operated projects. Automation technology is available to reduce losses even further.

Another primary water loss is seepage from unlined canal systems constructed through highly permeable soils, gravel, and rock. Seepage occurs because of the combined action of the forces of gravity and the attraction of soil for water. The force of the attraction of soil for water dominates where water is first turned into an earthen canal. The attraction for water is both horizontal and vertical in the soil surrounding the canal. For example, the soil's attraction for water may cause water to rise in the soil adjacent to the canal to a height above the water level in the canal. Consequently, the canal can loose a large amount of water because of capillary forces of the soil around the canal.

After water has been supplied to the canal for a period of time, a primary means of water loss through the soil is steady state seepage. Seepage can be vertical or horizontal depending on the hydraulic properties of the soil underlying the canal. If soils below the canal

have a high unsaturated conductivity, the seepage from the canal will move primarily vertically downward. If a layer of soil with low hydraulic conductivity is below the canal, the seepage may spread laterally perpendicular to the canal. If a water table is close to the bottom of the canal, the water will also spread laterally to a great extent.

The rate of seepage is determined by the hydraulic conductivity of the soil in and around the canal and by the head available. If the soil surrounding the canal is a nonfracturing clay, the conductivity is generally very low and the conveyance loss could be expected to be quite low. If a canal cuts through a sandy, gravelly, or porous rock region, the conveyance loss could be very high in the affected region. The hydraulic head available for seepage from the canal depends on the height of water in the canal and the depth to a permanent or perched water table.

Other factors also affect the seepage losses from canal systems:

- Length of time the canal is in operation
- Amount of turbidity and sediment in canal water
- Temperature of the water and the soil
- Barometric pressure
- Salt concentration of the water and soil
- Amount of entrained air in the water and soil
- The presence of certain biological factors

Because all of these factors act simultaneously and some counteract the effects of others, the effect of all variables on the rate of seepage from a canal is difficult to predict.

Seepage loss from pipelines and lined canals depends on the type of pipe or lining used and the care taken when installing and maintaining the delivery system. If properly selected, installed, and maintained, the seepage losses through pipelines and linings generally are insignificant. Seepage losses through pipelines and lined canals often occur at faulty or broken sections of the system. Conveyance losses can also occur around gates, valves, turnouts, and other structures. However, if the structures are properly installed and maintained, these losses should also be minimal.

Considerable quantities of water can be lost to the consumptive use of phreatophytes and hydrophytes that grow in and next to the canal, especially in unlined canals. If the density of these plants becomes too intense or if they obstruct flow, corrective actions are generally required. For example, weeds in the canal can cause increased resistance to flow and reduced canal capacity. Also, if the weeds begin to float in the canal, they can eventually accumulate in a control structure and lead to control restrictions. If these water-loving plants cannot be eliminated or their presence is desirable, their consumptive use must be accounted for in the design and operation of the project.

The amount of water lost during conveyance can be measured on existing systems to estimate the efficiency. It may be possible to measure losses in prototype systems during the final design stages of a delivery system. In many cases the water loss during conveyance must be predicted. The most advanced methods of prediction use the soil's hydraulic properties at the canal location to solve complex flow equations through saturated and unsaturated media. If that information is not available or if time is not available to conduct detailed analysis, the conveyance efficiency can be estimated for representative systems. While this section is not a design guide for conveyance systems, the essence of these techniques is considered.

(1) Measuring conveyance efficiency

Four methods are commonly used to predict the conveyance efficiency for existing canals or when testing designs for proposed delivery systems. These methods are ponding tests, inflow-outflow tests, seepage metering, and hydraulic simulation. Each method has advantages and disadvantages, and no single method is better than any other. Unfortunately, none of the methods can be considered a standard that is extremely accurate. Two studies analyzed methods of measuring seepage losses and concluded that all methods can produce highly variable estimates (Hotes, et al. 1985 and Frevert and Ribbens 1988). However, the methods described below are the best techniques available and should be carefully conducted for dependable results.

Ponding test—A ponding test is commonly used on existing canal systems. This test is conducted by filling a reach of a canal to a depth greater than the normal flow depth. The rate of decline of the water level in the canal is recorded over time. The volume of seepage per unit of wetted surface area in the canal per unit of

time can be computed to determine the seepage rate. Units generally are cubic feet per square foot per day The rate of decline can then be prorated over similar reaches of the canal for the duration of the desired delivery. This gives an estimate of the amount of water that will be lost from the canal. The ponding test can also be conducted by adding known amounts of water to the canal to maintain a constant water level in the reach.

The ponding test has several disadvantages. The test cannot be conducted when the canal is supplying water for irrigation. Thus it must be completed before the start or after the end of the irrigation. The seepage rate from the ponded test may be inappropriate for the entire season because it can vary significantly over the irrigation period. The water in the pond is generally stagnate. Flowing water can affect the seepage rate of some soils. In addition the ponding test can be expensive if special dikes and bulkheads are necessary to restrict the flow. Filling the ponding test area can also be very involved when the irrigation project is not in operation.

Inflow-outflow method—The inflow-outflow method uses flow measurements at upstream and downstream locations along the canal to determine the losses in that reach of the canal. The inflow-outflow method can be easily used in canals where flow measuring devices have been designed into the system. All diversions and any input from rain must be considered when using the inflow-outflow method. The accuracy of the method generally improves with the length of the test and accuracy of the measuring structures.

Various methods of measuring flow in open channels have been developed that can work for the inflow-outflow method (Replogle and Bos 1982). Construction and installation of the flow measuring equipment can be expensive.

Seepage meter method—A seepage meter can be used to measure the seepage rate through very small parts of the canal system. The meter includes a small cylindrical bell. The open end of the bell is forced into the bottom or side of a canal. The closed end is connected to a water supply outside the canal. The hydraulic head of the water supply to the bell is maintained at the water level in the canal or is allowed to free fall. The rate that water seeps through the bell is measured and converted to an equivalent seepage rate for the canal.

The advantage of using a seepage meter is that it can be installed in flowing canals and is the simplest and least expensive test to conduct. However the accuracy of the test is very dependent on the installation of the meter. If the meter significantly disturbs the canal, a large error can result. Results from the seepage meter should only be applied to similar sections of the canal. The meter generally is limited to use in earthen canals in which the soil is suitable to form a seal around the bell as it is forced into the soil. The seepage meter can be washed away in sandy or gravelly soils.

Hydraulic simulation method—A hydraulic simulation method can be used to estimate the rate of seepage from a canal. It can be applied either before or after the canal has been constructed. This method depends on accurately measuring the soil's hydraulic properties in and around the canal. These properties are used in simulation models of the waterflow through saturated and unsaturated media to estimate the seepage loss (Bouwer 1988).

The advantage of using a hydraulic model is that various canal locations and designs can be readily evaluated before they are in place. The model also can simulate long-term conditions that may be impossible with other methods. This can be important if a soil layer below the canal limits seepage rather than those near or on the floor of the canal.

(2) Estimating conveyance efficiencies

Because measuring water losses in canals and other delivery systems can be difficult and inexact, the conveyance efficiency generally can be estimated for initial design and planning of irrigation projects. Several efficiency terms have been used depending on where the delivery system is located. Doorenbos and Pruitt (1977) divide the efficiency of an irrigation project into three components: supply conveyance efficiency (E_c), field canal efficiency (E_b), and field application efficiency (E_a). Conveyance efficiency and field canal efficiency are sometimes combined and called the distribution efficiency (E_d), where $E_d = E_c \times E_b$. The combination of the field canal and application efficiencies is often called the farm efficiency (E_f), where $E_f = E_a \times E_b$. The application efficiency can be estimated from the methods described earlier in this section.

Factors affecting conveyance efficiency include

- the size of the irrigated area,
- type of delivery schedule used to deliver water,
- the crops, the canal lining material, and
- the capabilities of the water supplier.

The field canal conveyance efficiency is primarily affected by the method and control of operation, the type of soils the canal transects, the length of the canal, and the size of the irrigated block and fields. The farm efficiency is very dependent on the operation of the supply system relative to the supply required on the farm. Doorenbos and Pruitt (1977) present approximate efficiencies for various conditions as summarized in table 2–53.

A procedure used in the Washington State Irrigation Guide can also be used to estimate seepage losses (USDA 1985). The method gives a range of expected seepage losses depending on the transport material in the delivery system (figure 2–50). The range is dependent on the amount of fines in the material. In addition, the following losses may be expected:

Ditchside vegetation	0.5-1% loss per mile
Buried pipeline	0.01 – 0.15 ft^3/ft^2, depending on the age and type of pipe.

Example 2–27 shows the calculations for seasonal water loss in an earthen ditch.

Example 2–27 Seepage loss

Given:

Soil	Loam
Ditch length	1,320 ft.
Flow area	2.5 ft^2/ft (measured wetted perimeter)
Time	water in the ditch 180 days
Stream size	2.5 ft^3/s

Determine: Seasonal water loss

Solution: Use figure 2–50 to find the seepage loss of a loam soil:
= 1.23 $ft^3/ft^2/d$

Use average values to compute the seepage loss:

$$= \frac{\text{Flow Area} \times \text{Length} \times \text{Loss} \times \text{Time}}{43{,}560 \text{ ft}^2 \text{ / acre}}$$

$$= \frac{2.5 \times 1320 \times 1.23 \times 180}{43{,}560} = 16.8 \text{ acre feet}$$

Vegetation loss at 1 percent of the total flow for the period per mile:

= % x Flow x Days x Length (miles) x 2 acre $ft/ft^3/s/d$
= 0.01 x 2.5 x 180 x 1320/5280 x 2
= 2.25 acre feet

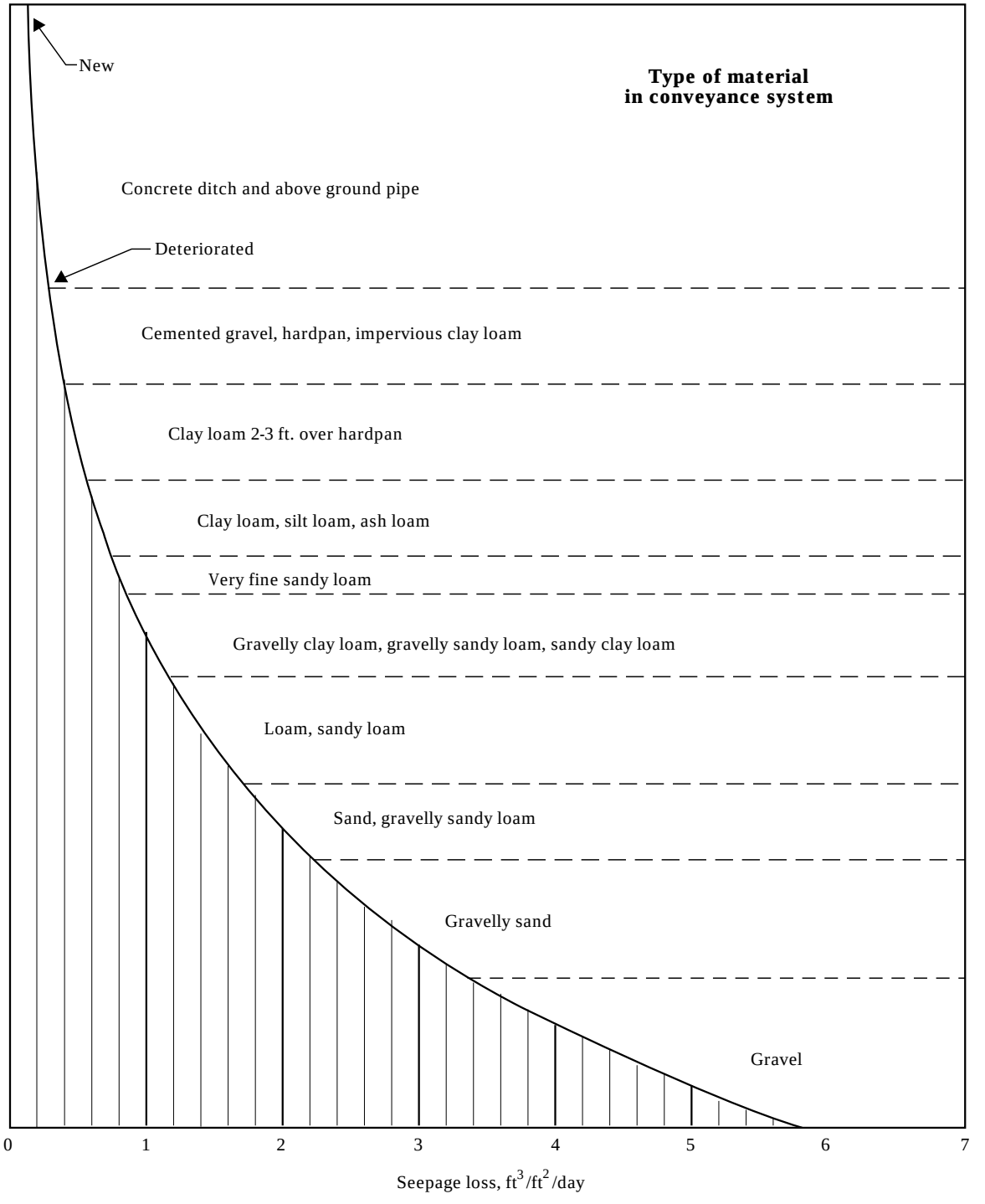
Total loss = Seepage loss + Vegetation loss
= 16.8 + 2.25 = 19.1 ac ft/yr

The accuracy with this method is no better than 0.5 acre feet, so the estimated loss is 19 acre feet per year.

Table 2–53 Conveyance, field, and distribution efficiencies for various types of systems (from Doorenbos and Pruitt 1977)

Characteristics	Efficiency
Project characteristics	Conveyance efficiency
Continuous supply with no substantial change in flow	90%
Rotational supply for projects with 7,000 to 15,000 acres and rotational areas of 150 to 800 acres and effective management	80%
Rotational supply for large projects (> 25,000 acres) and small projects (< 2,500 acres) with problematic communication and less effective management:	
Based on predetermined delivery schedules	70%
Based on arranged delivery schedules	65%
Irrigation field characteristics	Field efficiency
Irrigated blocks larger than 50 acres with:	
Unlined canals	80%
Lined canals or pipelines	90%
Irrigated blocks smaller than 50 acres with:	
Unlined canals	70%
Lined canals or pipelines	80%
For rotational delivery systems with management and communication adequacies of:	Project/district distribution efficiency
Adequate	65%
Sufficient	55%
Insufficient	40%
Poor	30%

Figure 2–50 Method to estimate seepage losses from irrigation delivery systems (adapted from USDA 1985)



623.0210 Onfarm irrigation requirements

(a) Net seasonal irrigation requirements

(1) Leaching not required

Predicting the seasonal irrigation requirement is important in planning and designing irrigation systems, allocating water supplies, and managing irrigation in saline areas. For those areas where salinity is not a problem, the determination of net irrigation can be calculated by rearranging the soil water balance in equation 2–83:

$$F_n = ET_c - P_e - GW - \Delta SW \qquad [2–106]$$

where:

F_n = net irrigation requirement for the season
ET_c = crop evapotranspiration during the season
P_e = effective precipitation during the season
GW = ground water contribution during the season
ΔSW = soil water depleted during the season

The time step used to calculate F_n ranges from a daily to a monthly basis. For planning purposes, a monthly basis is generally used. However, with the widespread use of personal computers, a daily water balance is often used in the many calculations required to evaluate each of these terms. A monthly water balance is used in example 2–28 to illustrate the combined procedure.

Example 2–28 Seasonal irrigation requirement when leaching is unnecessary

Given: A sandy loam soil that has a water table 5 feet below the crop root zone. The root zone is 4 feet deep. Salinity is not a problem. Average annual precipitation is 24 inches.

The field is irrigated with a center pivot irrigation system equipped with low-angle impact sprinklers. The normal application depth is 1.25 inches of water per irrigation, and the application efficiency is 80 percent. The crop is irrigated when the soil water depletion is 50 percent. The crop is generally irrigated twice per week in July and August and once per week in June and September.

Corn is generally planted on May 1 and harvested on October 1. Basal crop coefficients for the crop were calculated in section 623.0204(b).

Average monthly data

Month	ET_o (in/mo)	Precipitation (in/mo)	Interval between rains (d)	Basal crop coefficient
May	5.6	3.6	6	0.25
June	7.2	4.6	7	0.76
July	8.4	2.9	8	1.20
August	7.1	3.3	6	1.20
September	4.9	3.1	10	0.68

Find: Determine the monthly and seasonal irrigation requirement.

Example 2–28 Seasonal irrigation requirement when leaching is unnecessary—Continued

Solution: 1. Compute the monthly crop evapotranspiration (ET_c)

$$ET_c = K_a ET_o$$

- Compute the average monthly crop coefficient using equation 2–66.

$$K_a = \overline{K_s}\,\overline{K_{cb}} + F_w\left(1 - \overline{K_{cb}}\right)A_f$$

- Because the soil is irrigated at 50 percent depletion, it is not effected by water stress and K_s = 1.0.

- The mean value of K_{cb} can be taken as the value of K_{cb} at the middle of the month as computed in 623.0204(b) and listed above.

- For a center pivot that has impact sprinklers, F_w = 1.0.

- Values of A_f are in table 2–30. They depend on the wetting frequency and the soil type. For the irrigation and rainfall frequencies given above and the sandy loam soil, the values of A_f are:

Month	Minimum wetting interval (days)	A_f
May	6	0.321
June	7	0.275
July	4	0.482
August	4	0.482
September	7	0.275 - irrigated once a week

- The average crop coefficient (K_a) and crop evapotranspiration (ET_c) for the months are:

Month	K_a	ET_o in/mo	ET_c in/mo
May	0.49	5.6	2.7
June	0.83	7.2	6.0
July	1.20	8.0	9.6
August	1.20	7.0	8.4
September	0.77	4.9	3.8

Example 2–28 Seasonal irrigation requirement when leaching is unnecessary—Continued

2. Calculate the effective precipitation.

   - Use ET_c rates and rainfall amounts to calculate effective precipitation for an irrigation application of 1.25 inches. As an example for May, ET_c for corn = 2.7 inches and rain is 3.6 inches. From table 2–43, or equation 2–84, the effective precipitation is 2.24 inches.

   - Multiply that value by the factor (0.77) for a 1 inch net irrigation application (equation 2–85). (Note: 1.25 inch gross irrigation times an 80 percent application efficiency = 1.0 inch.) The effective precipitation for May is 1.72 inches. Values for other months are summarized below.

Average monthly effective precipitation

Month	ET_o (in)	ET_c (in)	P_e (in)
May	5.6	2.7	1.7
June	7.2	6.0	2.6
July	8.4	9.6	2.1
August	7.1	8.4	2.2
September	4.9	3.8	1.6
Total		30.5	10.2

3. Upward flow rate for soil type 6 and a water table 5 feet deep is about 0.02 inch per day (fig. 2–42). Thus, upward flow for May through September will be about:

   0.02 in/d x 153 d = 3 in.

4. Soil moisture mining for a 4-foot deep root zone and 50 percent depletion will be about:

   4 ft x 0.5 x 1.5 in/ft = 3 in

5. Net irrigation requirement:

$$F_n = ET_c - P_e - GW - \Delta SW$$
$$F_n = 30.5 - 10.2 - 3 - 3 = 14.3 \text{ in}$$

6. Gross irrigation requirement:

$$F_g = \frac{F_n}{E_a} = \frac{14.3}{0.8} = 17.9 \text{ in}$$

(2) Leaching required

Example 2–29 examines the same conditions except it includes salinity control.

Example 2–29 Seasonal irrigation requirement when leaching is needed

Given:

Average annual surface runoff from rainfall (SP_a)	=	1.0 inch
Surface evaporation in nongrowing season (E_{os})	=	3.0 inches
Electrical conductivity of the irrigation water (EC_i)	=	3.0 mmho/cm
Salt tolerance threshold of corn (EC_t from table 2–34)	=	1.7 mmho/cm
Center pivot system with no runoff of irrigation water (F_{ro})	=	0.0

Find: Determine the gross irrigation requirement.

Solution: Calculation of leaching requirement (L_r):

1. Use EC_t/EC_i to obtain an initial estimate of L_r.

$$\frac{EC_t}{EC_i} = \frac{1.7}{3.0} = 0.57$$

Using curve 3 in figure 2–33, an initial estimate of L_r is 0.28.

2. Calculate F_i using equation 2–77 with P_{net} computed using equation 2–78

$$P_{net} = P_a - SP_a - E_{os}$$

$$P_{net} = 24.0 - 1.0 - 3.0 = 20 \text{ in}$$

Then using equation 2–77 gives:

$$F_i = \frac{ET_c}{1 - L_r} - P_{net} = \frac{30.5}{1 - 0.28} - 20 = 22.4$$

3. Calculate EC_{aw} (equation 2–79).

$$EC_{aw} = \frac{EC_i\ F_i}{\left(F_i + P_{net}\right)}$$

$$= \frac{3.0\left(22.4\right)}{\left(22.4 + 20\right)} = 1.58$$

4. Calculate EC_t/EC_{aw}.

$$\frac{EC_t}{EC_{aw}} = \frac{1.7}{1.58} = 1.08$$

From figure 2–33, L_r = 0.17.

5. Go to step 2 and repeat calculations.

$$F_i = \frac{ET_c}{1 - L_r} - P_{net} = \frac{30.5}{1 - 0.17} - 20 = 16.7$$

Example 2–29 Seasonal irrigation requirement when leaching is needed—Continued

Solution (cont.):

6. New EC_{aw} value.

$$EC_{aw} = \frac{EC_i\ F_i}{\left(F_i + P_{net}\right)}$$

$$= \frac{3.0\left(16.7\right)}{\left(16.7 + 20\right)} = 1.37$$

7. Determine ratio of EC_t to EC_{aw}.

$$\frac{EC_t}{EC_{aw}} = \frac{1.7}{1.37} = 1.24$$

$$L_r = 0.15$$

$$F_i = 15.9 \text{ in}$$

8. New EC_{aw} value.

$$EC_{aw} = \frac{3\left(15.9\right)}{\left(15.9 + 20\right)} = 1.33$$

$$\frac{E_t}{EC_{aw}} = \frac{1.7}{1.33} = 1.28$$

$$L_r = 0.14$$

$$F_i = 15.5 \text{ in}$$

$$EC_{aw} = 1.31$$

Because the value of EC_{aw} is essentially the same for this iteration as that for the previous one, calculation of L_r and F_i can stop.

9. Calculation of gross irrigation from equation 2–80.

$$F_g' = \frac{F_i}{\left(1 - F_{ro}\right)} = \frac{15.5}{\left(1 - 0\right)} = 15.5 \text{ in}$$

Thus, salinity control under these conditions requires only 15.5 inches of gross irrigation.

Example 2–29 Seasonal irrigation requirement when leaching is needed—Continued

10. Calculate the gross irrigation required to meet crop evapotranspiration using equation 2–81.

$$F_g = \frac{\left(ET_c - P_e\right)}{E_a} = \frac{\left(30.5 - 10.2\right)}{0.8} = 25.4 \text{ in}$$

Thus in this case the irrigation requirements are determined by ET_c demands and not salinity control. A check of the procedure with this value of gross irrigation should be made to ensure accuracy:

$$EC_{aw} = \frac{3.0\left(25.4\right)}{\left(25.4 + 20\right)} = 1.68 \text{ mmho / cm}$$

$$\frac{E_t}{EC_{aw}} = \frac{1.7}{1.68} = 1.01$$

$$L_r = 0.18$$

$$F_g' = \frac{F_i}{\left(1 - F_{ro}\right)} = \frac{17.2}{\left(1 - 0\right)} = 17.2 \text{ in}$$

As F_g is > F_g', seasonal ET_c determines the gross irrigation requirements.

Now evaluate a situation for an arid area where salinity management determines the gross irrigation requirement (example 2–30).

Example 2–30 Seasonal irrigation requirement for an arid area

Given: Corn crop evapotranspiration = 26.0 inches
EC_t = 1.7 mmho/cm
EC_i = 2.0 mmho/cm
Center pivot irrigation with 10 percent runoff (F_{ro} = 0.10)
E_a = 0.8

Rainfall data: P_a = 12.0 inches P_e = 8.0 inches
SP_a = 1.0 inch E_{os} = 2.0 inches

Find: Determine the gross irrigation requirement.

Solution: From equation 2–78:

$$P_{net} = P_a - SP_a - E_{os} = 12 - 1 - 2 = 9 \text{ in}$$

Using these data with the iteration procedure for L_r as in the previous examples produces an L_r of 0.16, thus:

$$F_i = \frac{ET_c}{1 - L_r} - P_e = \frac{26}{1 - 0.16} - 9 = 22.0 \text{ in}$$

$$F_g' = \frac{F_i}{\left(1 - F_{ro}\right)} = \frac{22}{\left(1 - 0.10\right)} = 24.4 \text{ in}$$

$$F_g = \frac{\left(ET_c - P_e\right)}{E_a} = \frac{\left(26 - 8\right)}{0.8} = 22.5 \text{ in}$$

Thus in this case salinity management is the governing factor, and the average annual gross irrigation requirement is 24.4 inches.

Example 2–31 calculates the results of a surface irrigation system that has an irrigation efficiency of 60 percent and surface runoff of 20 percent.

Example 2–31 Seasonal irrigation requirement for a surface system

Given: The same data as that for the arid area gross irrigation example (example 2–30), except:
Application efficiency = 60%
Surface runoff = 20%

Find: Determine the gross seasonal irrigation requirement.

Solution: The needed leaching requirement is still 0.16 and the gross irrigation would be:

$$F_g' = \frac{22}{(1-0.2)} = 27.5 \text{ in}$$

$$F_g = \frac{18}{0.6} = 30 \text{ in}$$

In this case, the efficiency of the irrigation system indicates a higher gross irrigation requirement than required for salinity control.

(b) System capacity requirements

Along with to meeting the seasonal irrigation requirement, irrigation systems must be able to supply enough water to prevent crop water stress during a shorter time period. The system capacity is the rate of water supply that the irrigation system must provide to prevent water stress. The water supply rate (Q) is often expressed in units of inches per day or gallons per minute per acre (gpm/ac):

$$Qt = F_g A, \text{ so } \quad \frac{Q}{A} = \frac{F_g}{t} \qquad [2–107]$$

for common units:

$$\frac{Q, \text{gpm}}{A, \text{acres}} = 18.86 \frac{F_g, \text{ inches}}{t, \text{ days}}$$

where:
A = irrigated area
t = time to irrigate the field

The water supply rate can also be expressed as the total volume flow rate for a field by multiplying the capacity in gpm/acre times the area of the field.

The system capacity must account for crop need and the efficiency of the irrigation system. These computations are distinguished by the net system capacity (C_n) versus the gross system capacity (C_g). The net capacity is determined by the supply rate needed to maintain the soil water balance above a specified level that will reduce or minimize water stress. The gross capacity is the combined effect of crop needs and system inefficiency. Net and gross capacity are related by the application efficiency and the percentage downtime (D_t) for the system:

$$C_g = \frac{C_n}{E_a\left(1 - \frac{D_t}{100}\right)} \qquad [2–108]$$

where:
C_g = gross system capacity
C_n = net system capacity
E_a = application efficiency, expressed as a decimal
D_t = irrigation system downtime, %

The application efficiency used in equation 2–108 can be estimated for various systems using data from section 623.0209. The downtime is the amount of time the irrigation system is inoperable because of scheduled maintenance, breakdowns, moving or adjusting irrigation equipment, load management programs, and other management considerations. For example, if a system is inoperable 1 day per week, the percentage downtime would be 14 percent.

The capacity described in equation 2–108 does not include onfarm conveyance losses. If the irrigation delivery system for the farm contains major losses, then the capacity needed at the delivery point on the farm should be increased as discussed in 623.0209(e).

The conveyance efficiency (E_c) is used to compute the losses in the delivery system such that the farm capacity (C_f) can be computed:

$$C_f = \frac{C_g}{E_c} \qquad [2–109]$$

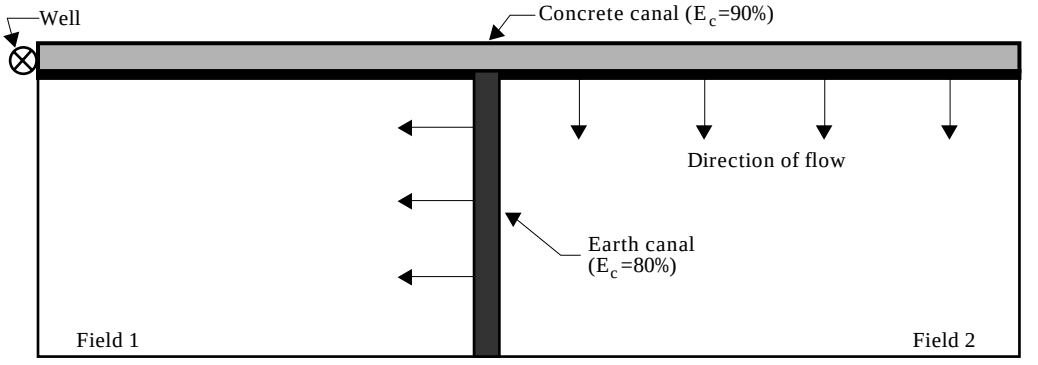
where:
C_g = gross capacity for each field
E_c = conveyance efficiency

Example 2–32 illustrates the use of equation 2–109.

Pipelines generally have a high conveyance efficiency that can be reliably estimated. The conveyance efficiency of canal delivery systems varies greatly especially for earthen canals. A range of conveyance efficiencies for various delivery systems is given in table 2–53.

Example 2–32 Farm capacity

Given: A farm has an irrigation system with a net capacity of 0.3 inch per day. It has two fields as shown below. Each field is 80 acres and is irrigated with siphon tubes. The application efficiency is 65 percent for both fields. The system is shut down about 10 percent of the time.



Find: Determine the discharge needed from the well.

Solution:

1. Net capacity for the farm is expressed in inches per day. Use equation 2–107 to convert to flow rate per unit area (gpm/ac):

$$C_n = 0.30 \text{ in / d} \times 18.86 = 5.7 \text{ gpm / acre}$$

2. The gross capacity for each field is (equation 2–108):

$$C_g = \frac{5.7 \text{ gpm / ac}}{0.65 \times (1 - 0.1)} = 9.7 \text{ gpm / ac} \times 80 \text{ ac} = 780 \text{ gpm}$$

3. However, the losses in the conveyance system must also be supplied by the pump. The discharge needed at the turnout into the earth canal for Field 1 should be:

$$C_{f1} = \frac{780 \text{ gpm}}{0.80} = 975 \text{ gpm}$$

The discharge for the concrete canal supplying Field 2 would be:

$$C_{f2} = \frac{780 \text{ gpm}}{0.90} = 867 \text{ gpm}$$

The well must supply the total flow to each field plus the loss in the main supply canal:

$$C_f = \frac{(975 + 867)}{0.90} = 2{,}047 \text{ gpm}$$

So the well and pump should supply about 2,050 gpm.

(c) Net system capacity

Determining the net system capacity is generally the most difficult process in computing irrigation supply rates. Irrigation systems must supply enough water over prolonged periods to satisfy the difference between evapotranspiration demands and rainfall. Water stored in the crop root zone can supply part of the crop demand. However, the volume of water that can be extracted from the soil cannot exceed the amount that will induce crop water stress.

A careful accounting of the soil water status is required if soil water is used to supply crop water needs when the crop evapotranspiration demands are larger than the irrigation system capacity plus rainfall. Some irrigation designs have been developed to completely meet peak ET_c needs without reliance on either rain or stored soil water. Other design techniques intentionally rely on stored soil water to meet crop requirements. Each method is reviewed in the following subsections.

(1) Peak evapotranspiration methods

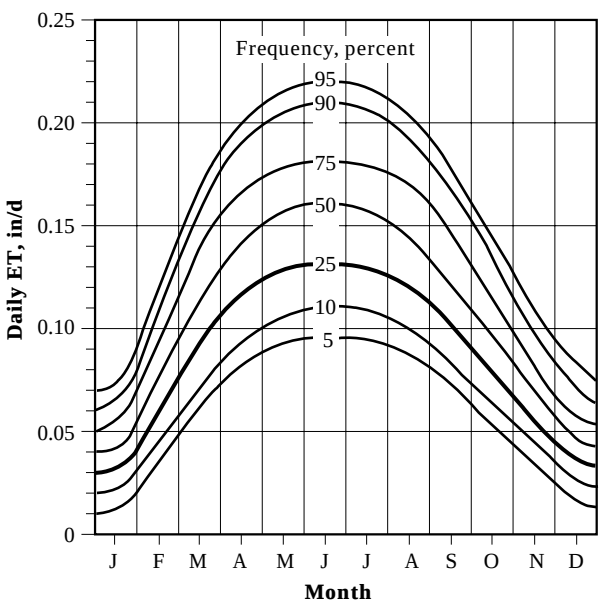
The most conservative method of designing irrigation systems is to provide enough capacity to meet the maximum expected or "peak" evapotranspiration rate of the crop. In this case rain and stored soil moisture are not considered in selecting the system capacity. This design procedure relies on determining the distribution of ET_c during the year for the principle irrigation crops. The ET_c during the season varies from year to year (fig. 2–51). For this example, the peak ET_c occurs in late June and early July. The mean ET_c during this period is about 0.16 inch per day. However, the ET_c is higher than 0.16 inch per day half of the time, and an irrigation system should be designed accordingly with a capacity larger than 0.16 inch per day.

The daily ET_c for ryegrass shown in figure 2–51 is less than 0.21 inch per day about 90 percent of the time and less than 0.22 inch per day about 95 percent of the time. In other words, if a system was designed with a net system capacity of 0.22 inch per day, the system could be expected to supply enough water to avoid crop water stress 95 percent of the time, or 19 out of 20 years. Because peak ET_c methods disregard rain and stored soil moisture, the capacity at the 90 percent frequency or probability level would be adequate for design. For the example in figure 2–51, the net system capacity should be about 0.21 inch per day, or about 4 gpm per acre.

The ET_c frequency distribution shown in figure 2–51 is for daily ET_c. The average ET_c for the period between irrigations decreases as the length of the time between irrigations increases (as explained in section 623.0203, figure 2–14). Using the 90 percent frequency for a field that is irrigated weekly (i.e., 7–day period in fig. 2–14), the average daily ET_c rate would be reduced to 0.19 inches per day, giving a peak capacity of 3.6 gpm per acre. Thus, by designing for the anticipated interval between irrigations, the system capacity could be reduced by about 10 percent. This reduction in capacity can save irrigation development costs, especially for permanent canal based systems.

Designing for peak capacity depends on the ET_c frequency distribution. The ET_c during the peak ET_c time period can be computed using the procedures presented in section 623.0203 of this chapter. Climatic data from at least 10, and preferably more, years should be used to compute the ET_c distribution. The computed ET_c must be analyzed to determine the ET_c rate for the appropriate design probability.

Figure 2–51 Frequency distribution of mean daily ET_c of ryegrass for each month in a coastal California Valley (adapted from Doorenbos and Pruitt 1977)



Generally, an extreme value analysis is used with the distribution of the annual maximum ET_c to determine the peak ET_c for design. To use an extreme value analysis, the maximum ET_c for each year is determined. The maximum annual ET_c values are then ranked in ascending order, and the probability of each ET_c value is computed as:

$$P_b = 100\left(\frac{m}{n+1}\right) \qquad [2–110]$$

where:
P_b = probability that the ET_c will be less than a specified value
m = rank of an ET_c value (m=1 for the smallest ET_c data value)
n = number of years analyzed.

Example 2–33 illustrates the process.

Once the probability has been computed, the data can be plotted and a smoothing procedure used to better extrapolate the data to the design value. The annual extreme ET_c data generally requires a specialized frequency distribution to represent the data. Two distributions that commonly fit these types of data are the log-normal distribution and the Weibull distribution.

The *log-normal distribution* assumes that the logarithm of the maximum daily ET_c values is normally distributed. The log-normal distribution is a bounded distribution for $ET_c \geq 0$ and is skewed to the left of the mean ET_c. It can be analyzed using special graph paper where the ET_c data is plotted directly. If the data fit a log-normal distribution, it generally falls on a straight line on the special graph paper. The straight line can then be used to predict the design peak ET_c rate.

The probability data from the example 2–33 for maximum daily ET_c are graphed on the log-normal plot shown in figure 2–52. The best fitting straight line is used to determine the design peak ET_c rate for the selected probabilities. Typical design probabilities are 75, 80, 90, or 95 percent depending on the value of the intended crop.

For the data in figure 2-52, the design peak ET_c rates would be:

Design probability	Peak ET_c (in/d)
75	0.45
80	0.46
90	0.51
95	0.55

The *Weibull distribution* can also be used to analyze the extreme ET_c. This procedure is well described by James (1988). The probability of ET_c being smaller than a specified value is computed using the procedure described for equation 2–110. Then the Weibull transform of P_b is computed:

$$W = LOG\left[-LOG\left(\frac{P_b}{100}\right)\right] \qquad [2–111]$$

where:
W = the Weibull transform of P_b
P_b = probability ranging from 0 to 100
LOG = the base 10 logarithm

The Weibull transform of P_b is then plotted on regular graph paper, and the design peak ET_c rate is determined. The use of the Weibull method for the example data from James (1988) is illustrated in example 2–34.

Example 2–33 Peak evapotranspiration frequency analysis

Given: Assume crop coefficient (K_c) = 1.0 for this period. Pan coefficient (K_p) = 0.75.

Daily evaporation from a Class A evaporation pan, in/d

Day	Year 1	2	3	4	5	6	7	8	9	10
1	0.64	0.32	0.24	0.30	0.15	0.22	0.28	0.35	0.23	0.27
2	0.25	0.41	0.26	0.17	0.31	0.42	0.18	0.42	0.65	0.28
3	0.35	0.30	0.17	0.25	0.52	0.15	0.32	0.23	0.22	0.27
4	0.31	0.10	0.39	0.16	0.16	0.45	0.31	0.42	0.60	0.26
5	0.20	0.14	0.29	0.30	0.42	0.45	0.33	0.43	0.39	0.54
6	0.49	0.36	0.36	0.60	0.39	0.30	0.38	0.22	0.55	0.39
7	0.38	0.35	0.33	0.23	0.22	0.49	0.36	0.36	0.68	0.43
8	0.27	0.36	0.11	0.36	0.21	0.30	0.41	0.21	0.23	0.42
9	0.61	0.45	0.23	0.35	0.22	0.45	0.26	0.26	0.23	0.43
10	0.55	0.47	0.40	0.43	0.06	0.52	0.45	0.35	0.30	0.30

Find: Determine the peak ET_c rate for design.

Solution: Example calculation for day 1 of year 1:

$ET_o = K_p\ E_{pan}$ = 0.75 x 0.64 in/d = 0.48 in/d

$ET_c = K_c\ ET_o$ = 1.0 x 0.48 in/d = 0.48 in/d

The resulting daily ET_c for the crop is:

Daily crop evapotranspiration, in/d

Day	Year 1	2	3	4	5	6	7	8	9	10
1	0.48	0.24	0.18	0.23	0.11	0.17	0.21	0.26	0.17	0.20
2	0.19	0.31	0.20	0.13	0.23	0.32	0.14	0.32	0.49	0.21
3	0.26	0.23	0.13	0.19	0.39	0.11	0.24	0.17	0.17	0.20
4	0.23	0.08	0.29	0.12	0.21	0.34	0.23	0.32	0.45	0.20
5	0.15	0.11	0.22	0.23	0.31	0.34	0.25	0.32	0.29	0.41
6	0.37	0.27	0.27	0.45	0.29	0.23	0.29	0.17	0.41	0.29
7	0.29	0.26	0.25	0.17	0.17	0.37	0.27	0.27	0.51	0.32
8	0.20	0.27	0.08	0.27	0.16	0.23	0.31	0.16	0.17	0.32
9	0.46	0.34	0.17	0.26	0.17	0.34	0.20	0.20	0.23	0.23
10	0.41	0.35	0.30	0.32	0.05	0.39	0.34	0.26	0.23	0.23
An. max.	0.48	0.35	0.29	0.45	0.39	0.39	0.34	0.32	0.51	0.41

Ranking of annual maximum values (m)

	1	2	3	4	5	6	7	8	9	10
Annual maximums (in/d)	0.29	0.32	0.34	0.35	0.39	0.39	0.41	0.45	0.48	0.51
P_b	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9

Example 2–34 Weibull distribution

Given: The maximum annual ET_c or net irrigation requirement from James (1988) is listed in the table below.

Find: The design net irrigation requirement for design probabilities of 75, 80, 90, and 95 percent

Solution: The procedure to solve the problem is:

1) The net irrigation requirement data is ranked in ascending order.
2) The probability of a smaller ET_c than a specified value is calculated using equation 2–110.
3) Compute the Weibull transform (W) using equation 2–111.
4) Plot W versus the net irrigation requirement.
5) Determine the probable maximum ET_c from the best fitting straight line.

Maximum annual irrigation requirement (in/d)	Rank	P_b	W	Maximum annual irrigation requirement (in/d)	Rank	P_b	W
0.280	1	4.3	0.13	0.358	12	52.2	-0.55
0.291	2	8.7	0.03	0.358	13	56.5	-0.61
0.311	3	13.0	-0.05	0.370	14	60.9	-0.67
0.319	4	17.4	-0.12	0.382	15	65.2	-0.73
0.331	5	21.7	-0.18	0.382	16	69.6	-0.80
0.331	6	26.1	-0.23	0.382	17	73.9	-0.88
0.339	7	30.4	-0.29	0.390	18	78.3	-0.97
0.350	8	34.8	-0.34	0.390	19	82.6	-1.08
0.350	9	39.1	-0.39	0.402	20	87.0	-1.22
0.350	10	43.5	-0.44	0.402	21	91.3	-1.40
0.358	11	47.8	-0.49	0.429	22	95.7	-1.71

Sample data from James (1988).

Results of the analysis are listed in the following table and are plotted in figure 2–53. Based on the analysis the design probabilities are:

Probability	Design net irrigation requirement, (in/d)
75	0.38
80	0.39
90	0.41
95	0.44

Figure 2–52 Log-normal probability distribution to smooth extreme values for daily ET_c data (values plotted are the daily maximum data and the maximum 5-day average)

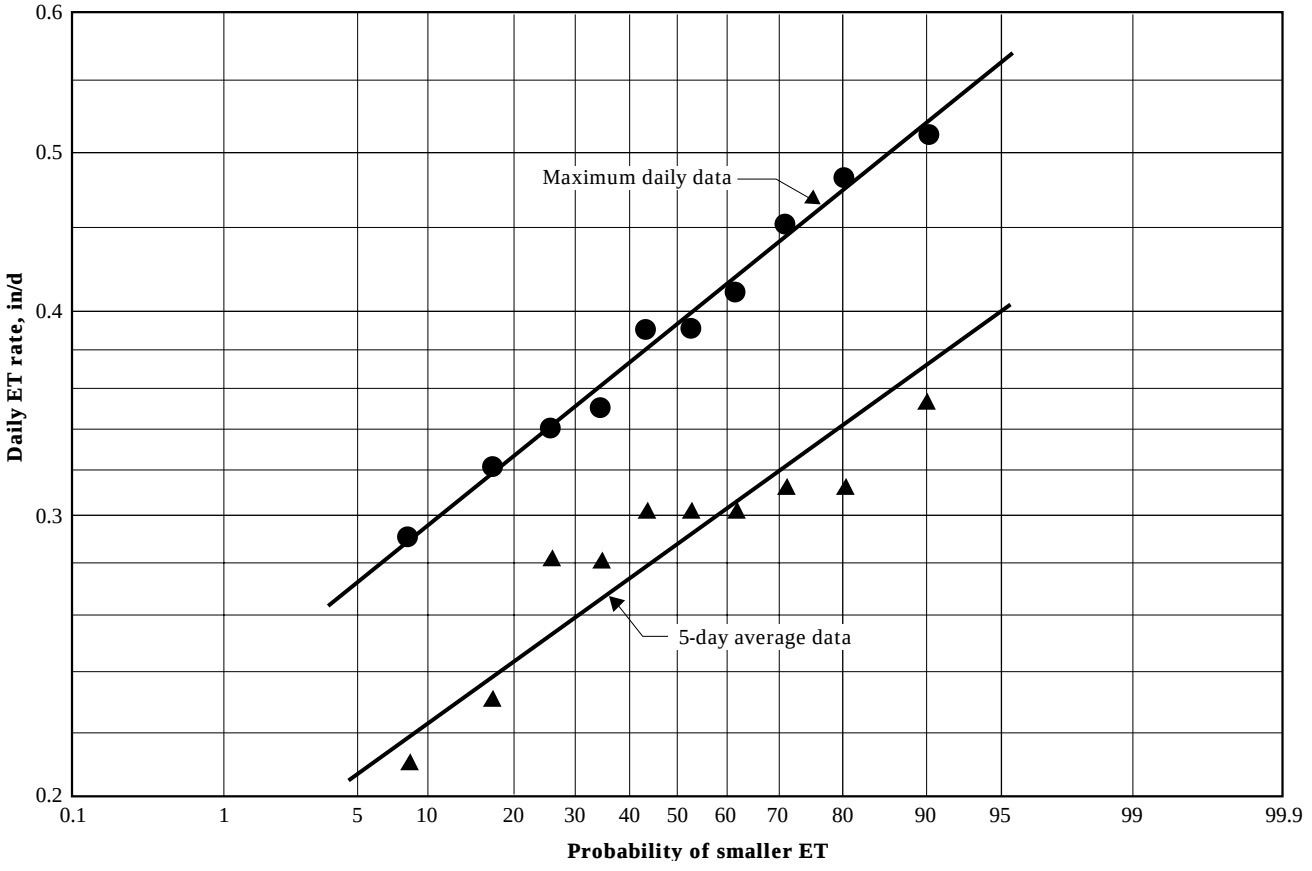
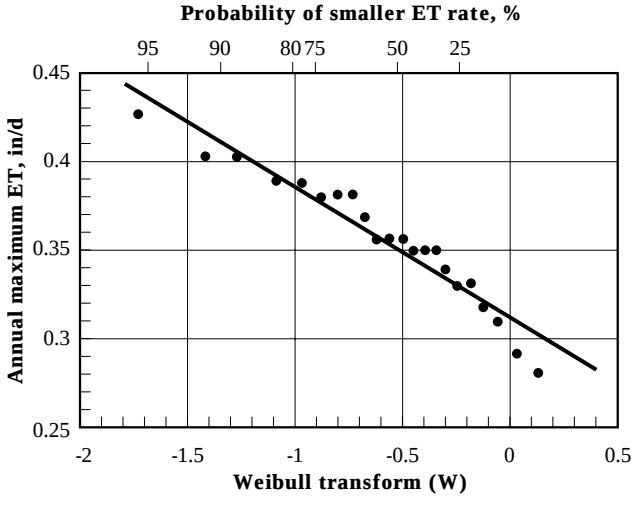


Figure 2–53 Weibull transform for smoothing annual maximum ET_c data to predict the design net capacity required



The data for daily maximum ET_c from the log-normal frequency analysis resulted in a relatively large design ET_c. If a field is irrigated less often than daily, the average ET_c for the appropriate period can be used in the frequency analysis. To illustrate this effect, the average daily ET_c for the first and last 5-day period for the 10 years of data used for the log-normal example are listed in table 2–54. The maximum 5-day average daily ET_c for each year is also shown.

The frequency analysis of the 5-day ET_c data is shown in figure 2–52. At a 90 percent probability level, the design ET_c rate drops from 0.51 inches per day for the daily maximum data to 0.36 inches per day for the 5-day average data. The examples shown in figure 2–52 were developed from a very limited amount of data. Actual analysis would require much more data. However, the examples show the dependence of the peak design ET_c rate on the length of the time period and illustrate the analysis procedure. The Weibull analysis could also be applied to maximum ET_c data for a given period or daily data.

Sometimes it is not possible to obtain enough climatic data to perform a frequency analysis of irrigation requirements. Doorenbos and Pruitt (1977) present a method (fig. 2–54) to predict the monthly peak ET_c from the mean monthly ET_c and the nominal irrigation depth for a probability level of 75 percent. In other words, the crop ET_c can be expected to be less than the determined value 3 out of 4 years. The use of Doorenbos and Pruitt (1977) method is illustrated in example 2–35.

Example 2–35 Peak evapotranspiration

Given: Mean monthly evapotranspiration for corn = 0.30 in/d
Semi-arid climate
Normal depth of irrigation = 2.2 in.

Find: The mean ET_c rate for the peak month

Solution: From figure 2–54, ratio of peak/mean monthly ET_c is 1.1
Then the peak ET_c = 1.1 x 0.30 in/d
= 0.33 in/d

A method to predict the daily peak period ET_c rate for general conditions is shown in table 2–55 (USDA-SCS 1970). This relationship should only be used for general estimates and where the previous peak ET_c methods cannot be applied.

(2) Soil water balance methods

The previous system capacity methods are based on selecting a system capacity that can supply water at a rate equal to the peak ET_c for a period. However, it is unlikely that several periods with water requirements equal to the peak ET_c will occur consecutively. The crop water use during the combined time period can come from the irrigation supply or from rain and stored soil water. Therefore, the capacity could be reduced if rain is likely or if stored soil water can contribute part of the ET_c demand.

Relying on soil water can reduce capacity requirements in two ways. First, the soil moisture can supply water for short periods when climatic demands exceed the capacity. The soil water used during the short period can be stored before it is needed or be replaced to some extent during the subsequent period when the ET_c demand decreases. Where the irrigation capacity is less than the peak ET_c rate, periods of shortage will occur when crop water use must come from the soil or rain (fig. 2–55). However, during other periods the capacity may exceed the ET_c, and the water supplied during the surplus period can replenish some of the depleted soil water.

Table 2–54 Average 5-day ET_c data for the log-normal frequency analysis data

Year	Average daily ET_c for days 1–5 (in/d)	6-10 (in/d)	Maximum annual 5-day ET_c rate, (in/d)
1	0.26	0.35	0.35
2	0.19	0.30	0.30
3	0.20	0.21	0.21
4	0.18	0.30	0.30
5	0.23	0.17	0.23
6	0.25	0.31	0.31
7	0.21	0.28	0.28
8	0.28	0.21	0.28
9	0.31	0.30	0.31
10	0.24	0.30	0.30

Figure 2–54 Ratio of mean peak and mean monthly ET_c for different climates during months of peak water use (adapted from Doorenbos and Pruitt 1977)

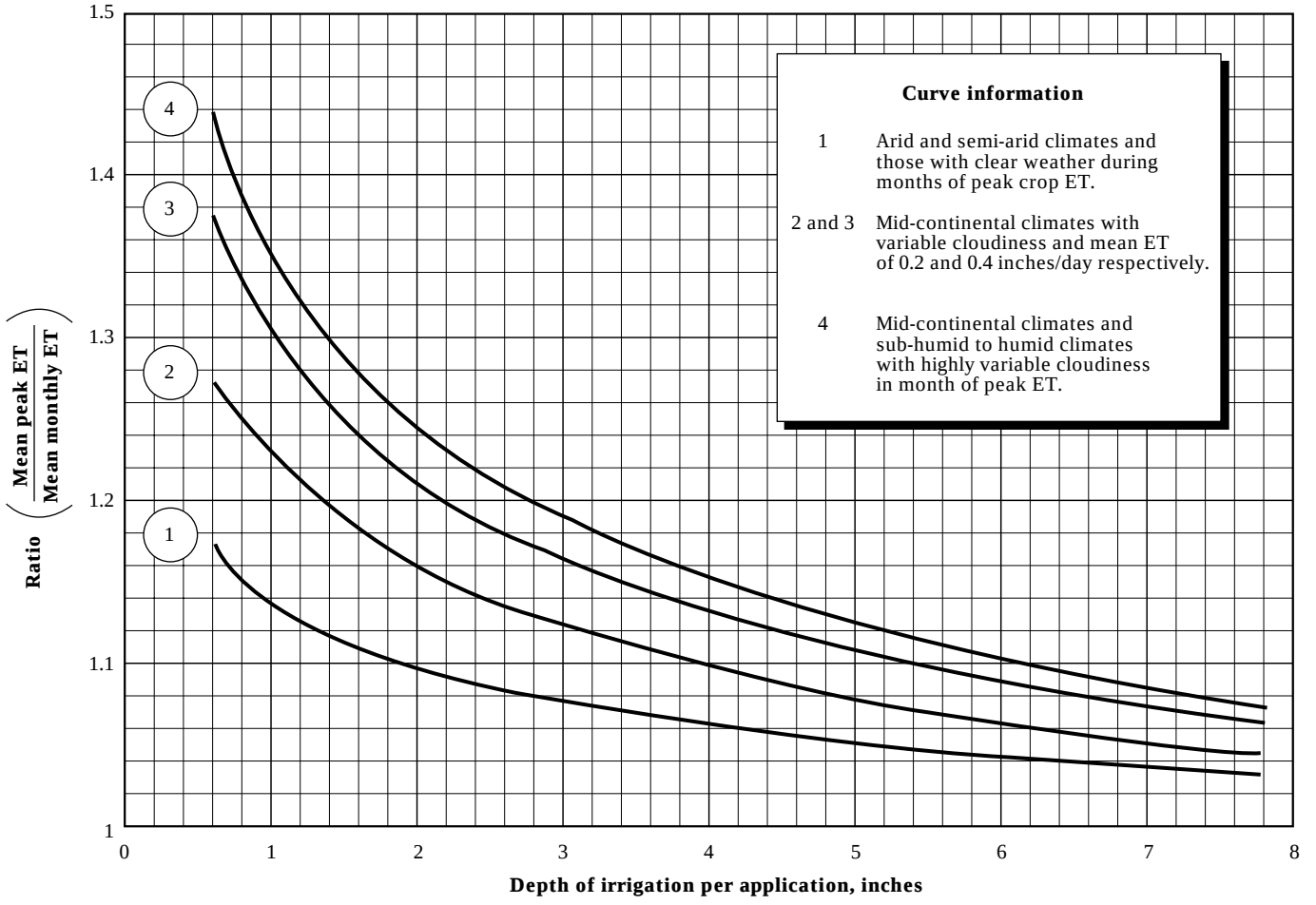
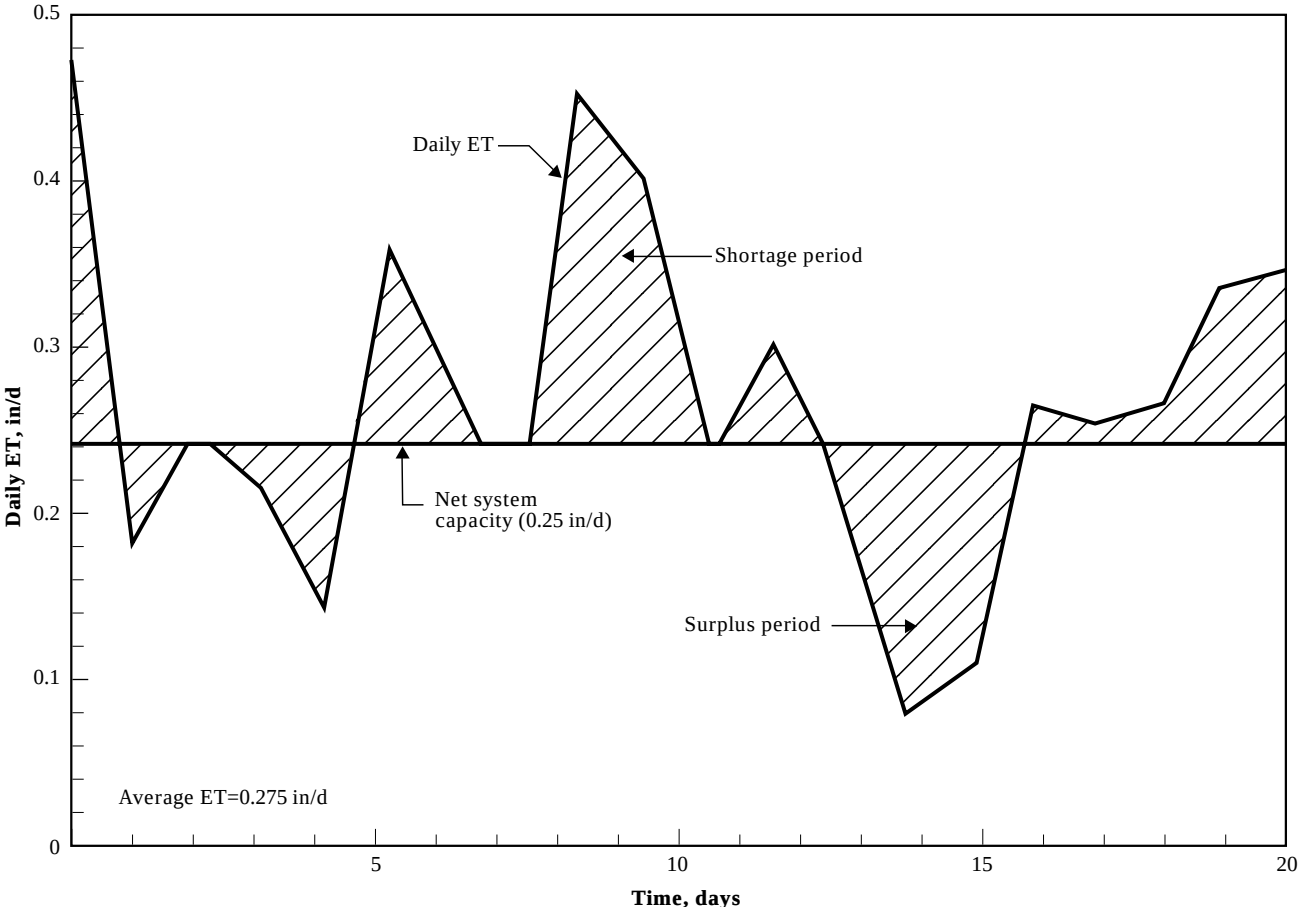


Figure 2–55 Shortage and surplus periods for a system where the capacity is less than the average ET_c during a peak water use period



The second way soil water can contribute to reduced capacity requirements is through a management allowable soil water depletion (MAD). This is the amount of water than can be depleted from the soil before crop stress occurs. The minimum capacity that maintains soil water above the allowable depletion during critical periods of the season can be used to design the irrigation system. An example of the effect of net capacity on soil water mining and the magnitude of soil water depletion during the season is shown in figure 2–56.

The positive bars in figure 2–56 represent the amount of rainfall and ET_c during 10-day periods. After mid-May ET_c exceeds rain. The deficit bars represent the difference between ET_c and rain. The largest 10-day deficit occurs in mid-July. If the use of soil water is not considered, the irrigation system would have to supply the deficit in that period. The peak 10-day irrigation requirement would be 3.3 inches per 10-days (or 6.24 gpm/acre). For the 130-acre field shown in figure 2–56, the net capacity requirement for the peak 10-day period would be 810 gpm. Using an 85 percent application efficiency, the gross capacity requirement would be about 950 gpm.

The amount of water that a 500 gpm capacity system with an 85 percent application efficiency can supply is also shown in figure 2–56. The net capacity for this system is:

$$C_n(\text{in / day}) = \left[\frac{\left(\frac{500\text{gpm}}{130\text{ac}}\right)}{18.86}\right] \times \frac{85}{100} = 0.17 \text{ in / day}$$

The 500 gpm capacity falls short of meeting the deficit in late June, and soil water stored would be depleted. The 500 gpm capacity falls short of the 10-day deficit from early in July through late in August, resulting in a cumulative depletion of 4 inches.

Suppose that the MAD before stress occurs is 3 inches for the crop and soil in figure 2–56. With the 500 gpm capacity system, the soil water would be depleted below the allowable level late in July, and the crop would suffer severe yield reduction. Obviously 500 gpm is inadequate for maximum yield at this site.

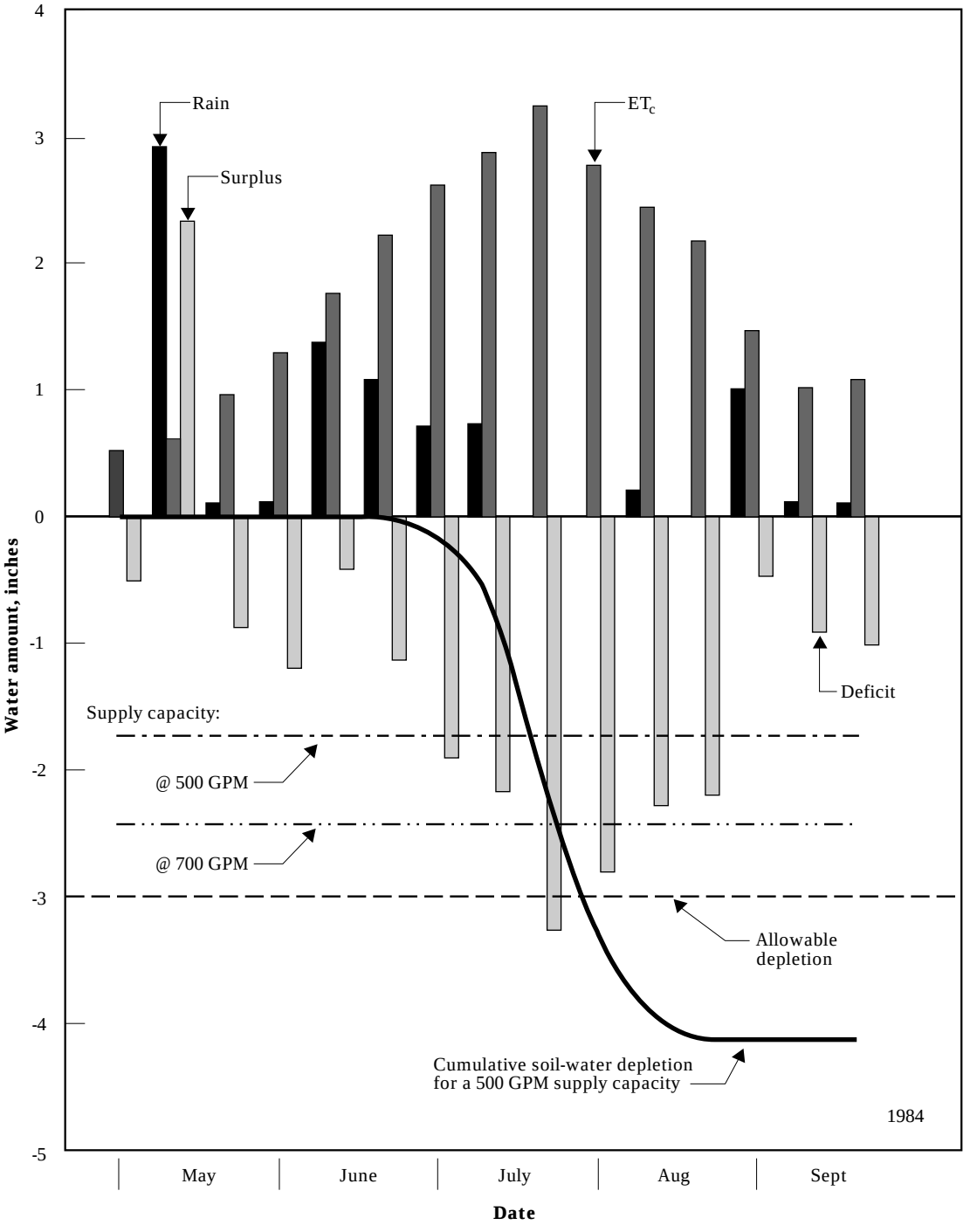
The net supply capacity for a 700 gpm system is also shown in figure 2–56. Here the system can supply the 10-day deficit for only the first 10 days in July. The cumulative soil water deficit for the 700 gpm system would be about 1.25 inches with proper management. That depletion is well above the MAD and should not reduce crop yield.

Table 2–55 Peak period average daily consumptive use (ET_d) as related to estimated actual monthly use (ET_m) (USDA 1970)

Net irrigation application F_n	Computed peak monthly crop evapotranspiration rate ET_m (in)[1/]																
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
(in)	Peak period daily evapotranspiration rate (in/d)																
1.0	.15	.18	.20	.22	.24	.26	.28	.31	.33	.35	.37	.40	.42	.44	.46	.49	.51
1.5	.15	.17	.19	.21	.23	.25	.27	.29	.32	.34	.36	.38	.41	.43	.45	.47	.50
2.0	.15	.16	.18	.20	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46	.48
2.5	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.39	.41	.43	.45	.47
3.0	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44	.46
3.5	.14	.16	.18	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46
4.0	.14	.15	.17	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
4.5	.14	.15	.17	.19	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
5.0	.13	.15	.17	.19	.21	.23	.25	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
5.5	.13	.15	.17	.19	.21	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
6.0	.13	.15	.17	.19	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.41	.43

1/ Based on the formula $ET_d = 0.034\ ET_m^{1.09}\ F_n^{-.09}$ (SCS 1970) where:
ET_d = average daily peak crop evapotranspiration for the period (in)
ET_m = average crop evapotranspiration for the peak month (in)
F_n = net irrigation application (in)

Figure 2–56 10-day ET_c, rain and soil water deficit and the soil water depletion pattern over a growing season as affected by gross system capacity (based on 130-acre field and 85 percent application efficiency)



This example shows that the maximum cumulative soil water depletion would be approximately 4, 1.25, and 0 inches for gross capacities of 500, 700, and 950 gpm, respectively. Clearly the opportunity to use available soil water substantially reduces the required system capacity.

Simulation programs using daily time steps to predict the soil water content have been used to determine the net system capacity when soil water is intentionally depleted. Some models, such as those by Heermann, et al. (1974) and Bergsrud, et al. (1982), use the soil water balance equation, such as equation 2–106, to predict daily soil water content. Others used crop simulation models to predict the net capacity to maintain soil water above the specified allowable depletion and the capacity needed to maintain yields above a specified percentage of the maximum crop yield (von Bernuth, et al. 1984 and Howell et al. 1989).

The capacities determined using soil water or crop yield simulation, or both, generally are dependent on the available water holding capacity of the soil. An example from the results of Heermann et al. (1974) is shown in figure 2–57. The allowable depletion of the soil profile must be determined to use the Heermann procedure. The allowable depletion is the product of the allowable percentage depletion and the available water in the crop root zone. The use of Heermann procedure for a sandy loam soil is illustrated in example 2–36.

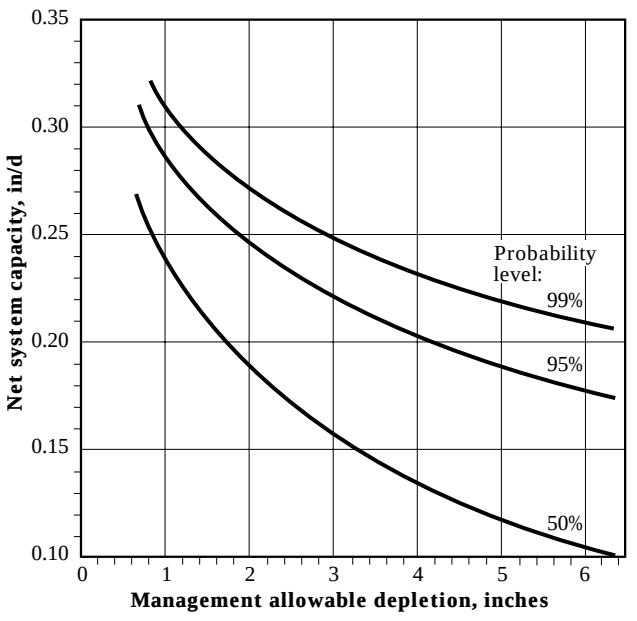
Example 2–36 System capacity for corn in eastern Colorado

Given:	A sandy loam soil that holds 1.5 inches of available water per foot of soil depth. Corn root zone depth of 4 feet. Management Allowable Depletion percentage equals 50 percent
Find:	The net system capacity needed at a 95 percent probability level.
Solution:	Allowable depletion = 1.5 in/ft x 4 ft x 0.50 = 3.0 in. From figure 2–57, the net capacity is about 0.22 in/d.

Like peak ET_c methods, net capacity determinations using soil water simulation require analysis of several years of data to define the design probability level. Data from the simulation models have been analyzed in two ways. Heermann, et al. (1974) used a version of an annual extreme value analysis. They kept track of the maximum annual soil moisture depletion for given capacities. Compiling these data for numerous years and analyzing using an appropriate statistical procedure gives the probability that the driest soil condition will be less than the specified allowable depletion.

R.D. von Bernuth, et al. (1984) kept track of the number of days that the soil water depletion exceeded the specified depletion. Combining several years of data provides a data base to develop the probability that the soil water depletion throughout the year will be less than the specified allowable depletion. Thus, the procedures are quite similar; only the probabilities have different meanings.

Figure 2–57 Design net capacity required for corn grown in eastern Colorado to maintain soil water depletion above a specified depletion for three design probabilities (adapted from Heermann, et al. 1974)



Others showed that the management strategies used to schedule irrigations affects the net capacity requirement (Bergsrud, et al. 1982 and von Bernuth, et al. 1984). If the strategy is to irrigate as soon as the soil will hold the net irrigation without leaching, the capacity will be smaller than if irrigation is delayed until the soil water reaches the allowable depletion. However, there are direct tradeoffs to the reduced system capacity. Delaying irrigation until the allowable depletion is reached results in more efficient use of precipitation and smaller seasonal irrigation requirements.

An example illustrates that the selection of an appropriate system design capacity must consider many factors (Bergsrud, et al. 1982). A well capable of producing 1,200 gpm has been installed. The static water level in the well is 30 feet, and the specific capacity is 30 gpm per foot of drawdown. The quarter section to be irrigated has a predominant soil type with a 4-inch available water holding capacity. A comparison of the two irrigation scheduling strategies is given in table 2–56.

The earliest irrigation date strategy has the advantages of lower initial cost and a lower demand charge on electric installations. The latest irrigation date strategy results in a lower seasonal water application and would appear to have an advantage with respect to electric load management programs because of the fewer hours of operation. The earliest date strategy also has an advantage in low-pressure applications because of lower system capacity and smaller application rates.

Table 2–56 Comparison of the effect of an earliest date and latest date irrigation strategy on system capacity and other performance criteria (adapted from Bergsrud et al. 1982)

	Earliest date	Latest date
Design capacity 90% level	0.226 in/d	0.266 in/d
System capacity 85% application efficiency—0% downtime	652 gpm	768 gpm
Total dynamic head 50 psi pivot pressure	182.2 ft	186.1 ft
Water horsepower	30.0	36.1
Brake horsepower @ 75% pump efficiency	40	48.1
Inches to be applied:		
Net	11.8	9.6
Gross	13.8	11.3
Hours of operation	1,238	861
Brake horsepower hours	49,520	41,414

(d) Irrigation scheduling

An important use of on-farm irrigation requirements is for irrigation scheduling. Irrigation scheduling is deciding when to irrigate and how much water to apply. Modern scheduling is based on the soil water balance for one or more points in the field. By estimating the future soil water content, irrigation can be applied before crop stress and after leaching would occur. Scheduling must involve forecasting to anticipate future water needs.

Several scheduling techniques and levels of sophistication can be applied to keep track of the amount of water in the crop root zone. A widely used method accounts for soil water similar to accounting for money in a checking account. The "checkbook" method depends on recording the soil water balance throughout the season. An example soil water balance sheet is shown in figure 2–58.

The date for future irrigations can be predicted if the average weekly water use rate is known. An example of average water use rates for three crops is shown in figure 2–59.

In some locations crop water use information is made available via newspapers, radio broadcasts, or telephone call-in systems. Any scheduling program should use rainfall measured at the field site. Rainfall amounts measured at the farmstead or in town are not good enough for scheduling because the spatial variability for rainfall is quite large. The checkbook method is simple and easily applied, but is tedious when several fields are considered. Also, forecasting can make bookkeeping cumbersome.

Irrigation scheduling can be fine tuned beyond the checkbook method using computers to calculate crop water use, evaluate alternatives, and consider system characteristics. The basic concept of the first developed computerized scheduling (Jensen, et al. 1971) is widely used today.

Most computer programs use a soil water balance, for one or more points in the field, to determine when to irrigate. The initial soil water depletion at the start of an update period must be known from either soil water measurement or previous calculations. Soil water depletion during the update period is calculated daily using crop evapotranspiration, rainfall, and irrigation. The deficit at the end of the update period provides the predicted status of the soil water depletion. Anticipated depletion for the future is then predicted for the forecast period using the long-term average water use rate. Irrigations are scheduled when available soil water drops below the MAD, which is often assumed to be 50 percent of the available water for the crop root zone.

To include an irrigation in the soil water balance, the net depth must be determined. The net depth depends upon the type of system. Usually sprinkler systems are operated to apply a known gross depth. Thus, the net depth is the product of the application efficiency and the gross depth.

Surface systems are often operated to refill the crop root zone, or that amount minus some rainfall allowance. The rainfall allowance, room for rain, is generally from 0.5 to 1.0 inches for fine textured soils and is generally not used for sandy soils. For surface systems, the net depth is often known and the gross depth is calculated using the net depth and an application efficiency.

Time required to apply the gross irrigation must be calculated to ensure that the entire field will be irrigated before stress occurs. This is often referred to as the cycle time or the irrigation frequency. This is the time required to apply the gross depth to the entire field with the given system capacity. For example, with a center pivot system, the starting position (fig. 2–60) is the location closest to the usual parking location of the pivot, or the first part to be irrigated. The starting position receives irrigation about 3 days before the last location irrigated (i.e., the stop position). The depletion at the stopping position can be greater than that for the starting position for a good part of the time as shown for a hypothetical period in figure 2–60.

For center pivots and other systems where the field can be irrigated frequently, separate soil water balances are kept for the starting and stopping positions. Combining the time required to irrigate the field and the forecasted depletion at the two positions allows computation of dates for starting irrigation to avoid stress or leaching. This range is described by the earliest and the latest irrigation dates.

Figure 2–58 Checkbook scheduling method (adapted from Lundstrom and Stegman 1988)

Soil-water balance sheet

Crop___________________________ Field ___________________ Emergence date ___________________________

Pumping capacity ____________________________ gmp/ac ______________________________________ net, in/d

Total available water _________________________ inches Rooting depth ______________________________ ft of soil

Allowable deficits: (30%) ______________ inch (50%) _______________ inch (70%) ________________ inch
for
Crop growth stages: _________________________ __________________________ __________________________

Week after emergence	Date	Soil-water field reading		Maximum temperature	Add	Subtract		Soil-water deficit	
		Pt. A	Pt. B		Crop water use	Rainfall	Net irrigation	Pt. A	Pt. B

Figure 2–59 Average daily water use during the season for three crops in North Dakota (adapted from Lundstrom and Stegman 1988)

Average daily water use for corn (in/d)

Maximum air temperature, °F	week 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
50-59	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.06	0.04	0.03
60-69	0.02	0.03	0.05	0.06	0.08	0.10	0.12	0.14	0.14	0.13	0.13	0.13	0.12	0.11	0.09	0.07	0.06
70-79	0.03	0.04	0.06	0.09	0.12	0.14	0.17	0.19	0.19	0.19	0.18	0.18	0.17	0.16	0.13	0.10	0.08
80-89	0.04	0.06	0.08	0.11	0.15	0.19	0.22	0.24	0.25	0.24	0.23	0.23	0.21	0.20	0.17	0.16	0.10
90-99	0.05	0.07	0.10	0.14	0.18	0.23	0.27	0.30	0.30	0.29	0.29	0.29	0.26	0.25	0.20	0.16	0.12
Growth stage		3 leaf				12 leaf	tassel	silk	polli-nate	blist. kernel	early dent			dent	mature		

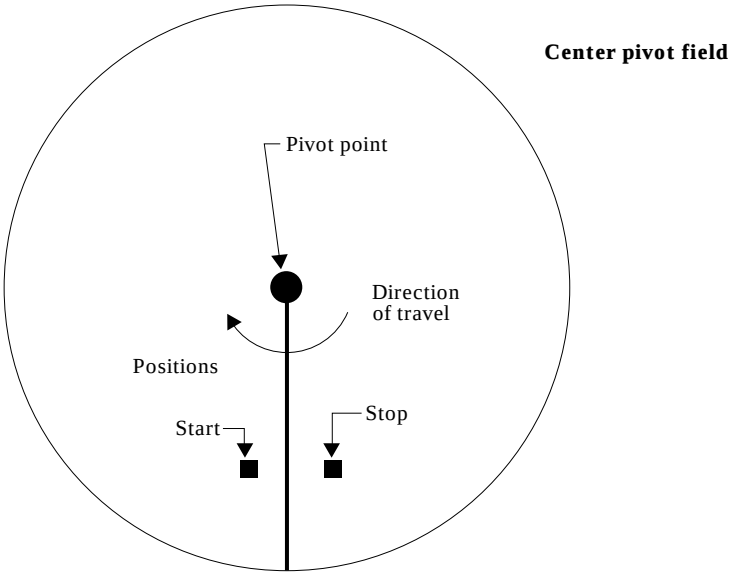
Average daily water use for wheat (in/d)

Maximum air temperature, °F	week 1	2	3	4	5	6	7	8	9	10	11	12	13	14
50-59	0.01	0.03	0.04	0.06	0.07	0.08	0.08	0.08	0.08	0.08	0.07	0.06	0.04	0.03
60-69	0.02	0.04	0.07	0.10	0.12	0.13	0.14	0.14	0.14	0.14	0.12	0.10	0.07	0.04
70-79	0.03	0.06	0.10	0.13	0.17	0.19	0.19	0.19	0.19	0.19	0.17	0.14	0.10	0.06
80-89	0.04	0.08	0.12	0.17	0.22	0.24	0.24	0.25	0.25	0.25	0.22	0.17	0.12	0.08
90-99	0.05	0.10	0.15	0.21	0.26	0.29	0.30	0.30	0.30	0.30	0.27	0.21	0.15	0.09
Growth stage			2 tiller		joint	boot	head	flower	early milk		early dough	hard dough		

Average daily water use for barley (in/d)

Maximum air temperature, °F	week 1	2	3	4	5	6	7	8	9	10	11	12	13
50-59	0.02	0.03	0.05	0.06	0.08	0.08	0.08	0.08	0.08	0.07	0.06	0.04	0.02
60-69	0.03	0.05	0.08	0.10	0.13	0.13	0.13	0.14	0.14	0.12	0.09	0.06	0.03
70-79	0.04	0.07	0.11	0.14	0.18	0.18	0.19	0.19	0.19	0.17	0.13	0.08	0.04
80-89	0.05	0.09	0.13	0.19	0.23	0.23	0.24	0.24	0.25	0.22	0.17	0.11	0.05
90-99	0.06	0.10	0.16	0.23	0.28	0.29	0.29	0.30	0.30	0.27	0.20	0.13	0.06
Growth stage			4–5 leaf				head			milk			

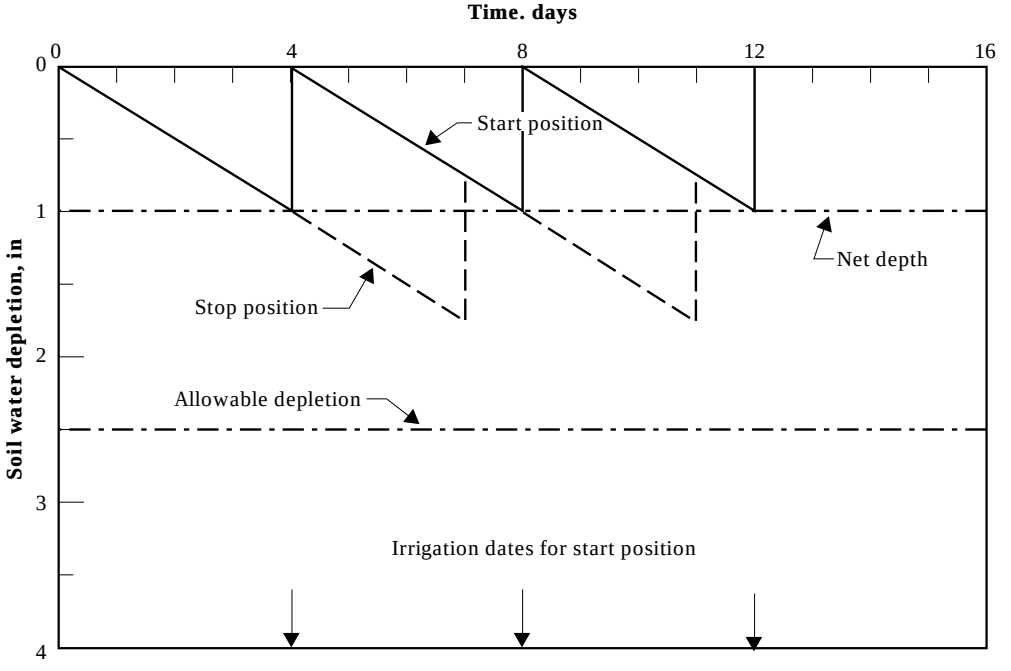
Figure 2–60 Irrigation cycle time, or irrigation interval, and its effect on the soil water depletion at the starting and stopping positions of an irrigation system (from Martin et al. 1991)



Given:

Cycle time = 3 days
Area = 130 acres
Application efficiency = 80%
Initial soil moisture depletion = 0

System capacity = 1,020 gpm
Gross depth = 1.25 inches
Net depth = 1.0 inches



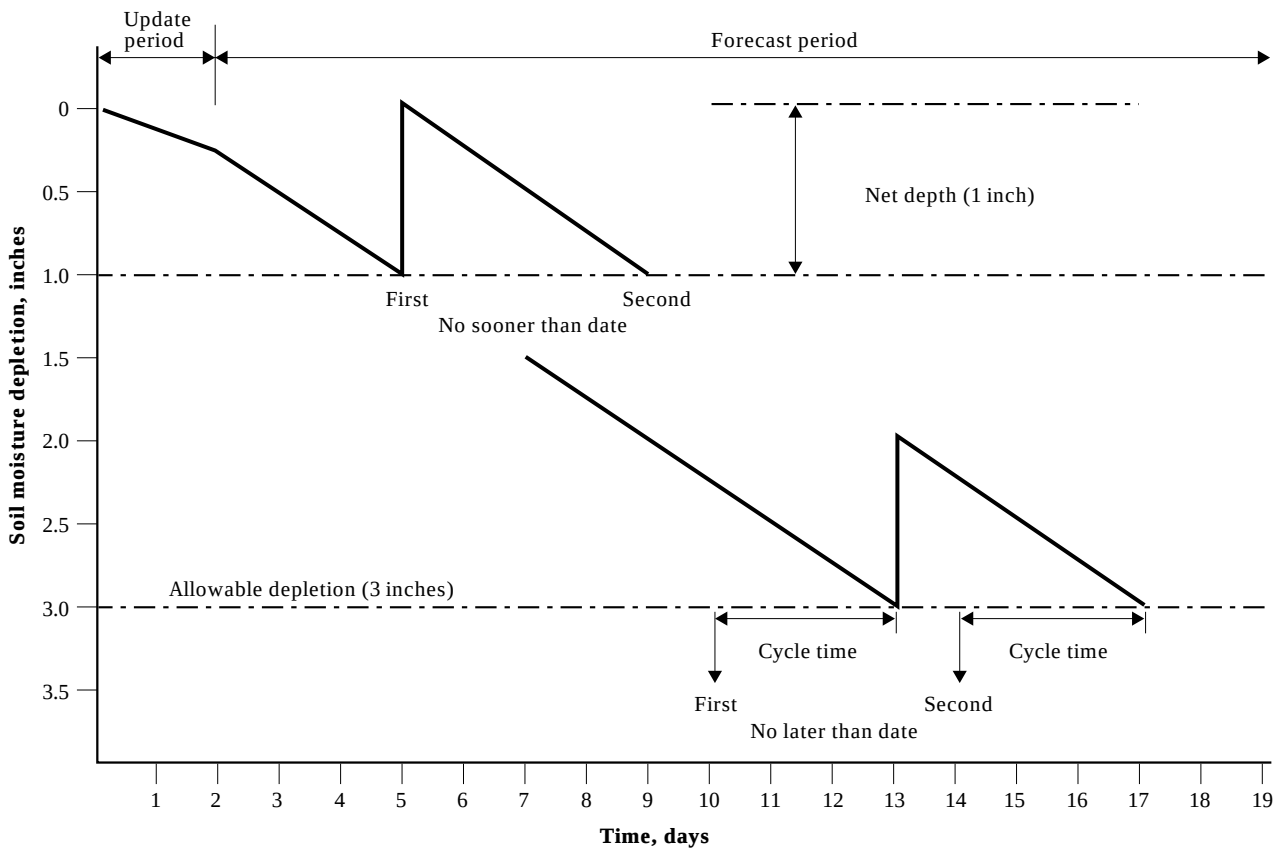
The earliest date corresponds to the earliest time the field will hold the net depth (fig. 2–61). The latest date represents the very latest time to irrigate so that the depletion will not exceed the allowable depletion. Example 2–37 helps to illustrate the scheduling process and the dependence on crop water use.

Some water management programs are based upon supplying farmers approximate ET_c rates for a region. The individual can then develop a schedule using a checkbook method based upon the regional ET_c rates for the update period, plus forecast ET_c rates. A regional ET_c form is shown in figure 2–62.

The scheduling procedures presented in this chapter are based on the soil water balance because those methods depend on estimating irrigation water requirements. These techniques depend on establishing an allowable soil water depletion to determine the latest time to irrigate. The allowable depletion depends on the crop, soil, and climate.

Field monitoring techniques can be used to establish the latest time to irrigate. Commonly used methods include measuring soil water potential, leaf water potential, and crop temperature. Each of these techniques must be calibrated for specific applications. Indices have been developed to quantify the effect of various monitoring results. Example indices are the stress day index method by Hiler and Clark (1971), the stress factor from Reddell, et al. (1987), and the crop water stress index by Jackson (1982). The use of these techniques is described by Martin, Stegman, and Fereres (1990).

Figure 2–61 Earliest and latest dates to irrigate for a system that applies 1 inch of net irrigation per application and has an allowable depletion of 3 inches, assuming the irrigation interval is 3 days (adapted from Martin, et al. 1991)



Example 2–37 Irrigation scheduling

Given:

Current depletion	= 0.5 in.	Field area (Area)	= 130 acres
Available water	= 1.5 in/ft	Normal cycle time (t)	= 72 hr
Current root zone depth	= 4 ft	Application efficiency	= 80%
Allowable depletion	= 50%	Forecasted ET_c rate	= 0.25 in/d
System capacity (Q)	= 900 gpm		

Find: Determine the earliest and latest irrigation dates.

Solution:

Gross depth	= Q x t / (453 x Area)	= 1.1 in.
Net depth	= Gross depth x Application efficiency	= 0.9 in.
Allowable deficit	= 1.5 in/ft x 4 ft x 0.5	= 3.0 in.

Earliest date	Start position	Stop position
Net depth (in.)	0.9	0.9
less current depletion (in.)	0.5	0.5
Remaining usable water (in)	**0.4**	**0.4**
Forecast ET_c rate (in/d)	0.25	0.25
Days until deficit > net depth	2	2
less cycle time, days	0	3
Earliest date to irrigate	**2**	**–1**

Answer: The earliest date is 2 days from now. If the field is irrigated sooner, drainage may occur at the start position. This assumes that the system was originally at the start position.

Latest date:	Start position	Stop position
Allowable deficit (in.)	3.0	3.0
less Current depletion (in.)	0.5	0.5
Remaining usable water (in.)	**2.5**	**2.5**
Forecast ET_c rate (in/d)	0.25	0.25
Days until deficit > allowed	10	10
less Cycle time (d)	0	3
Latest date to irrigate	**10**	**7**

Answer: The latest date to irrigate is 7 days from now. If the system is started any later, the stop position will become drier than the allowable deficit before the system can reach that point.

This section is a brief review of using crop water use requirements in scheduling irrigation. The methods to predict crop water use similar to those presented in this section are fundamental to modern scheduling.

The practical aspects of scheduling for various purposes are introduced (Martin, et al. 1990). The references cited in this section provide a list of additional reading on using crop water requirements for scheduling and on-farm irrigation management.

Figure 2–62 Example of regional ET_c data for irrigation scheduling

Regional scheduling data

Date	Reference crop ET (in/d)	Corn planted May 1 (in/d)	Corn planted May 15 (in/d)	Sorghum planted May 25 (in/d)	Soybean planted May 15 (in/d)	Alfalfa last cut July 1 (in/d)
July 15	0.32	0.29	0.26	0.21	0.22	0.29
July 16	0.28	0.25	0.23	0.18	0.20	0.26
July 17	0.23	0.21	0.19	0.15	0.17	0.22
July 18	0.27	0.25	0.22	0.18	0.20	0.26
July 19	0.15	0.14	0.13	0.10	0.11	0.15
July 20	0.12	0.11	0.10	0.08	0.09	0.11
July 21	0.35	0.24	0.30	0.25	0.27	0.35
July 22	0.42	0.41	0.37	0.30	0.32	0.42
July 23	0.40	0.39	0.35	0.29	0.31	0.40
July 24	0.38	0.38	0.34	0.28	0.30	0.38
July 25	0.31	0.31	0.28	0.23	0.25	0.31
July 26	0.24	0.24	0.22	0.18	0.19	0.24
July 27	0.22	0.22	0.20	0.17	0.18	0.22
July 28	0.35	0.35	0.33	0.27	0.29	0.35
Total	**4.04**	**3.89**	**3.52**	**2.87**	**3.10**	**3.97**

623.0211 Project water requirements

(a) Introduction

Determination of water requirements discussed in previous sections of this chapter have focused on individual fields where the water supply and other conditions did not limit operation of the irrigation system. Where multiple fields must be managed, a delivery schedule for the irrigated area must be developed. In some cases the irrigated area represents all or part of an irrigation project. In others it is a single farm where water delivery must be allocated to individual fields. In both cases a single source of water is available and must be supplied to each parcel of the irrigated area. Various methods have been employed to accomplish this distribution. The irrigation requirements of the crops are, of course, central to that consideration. It is assumed that the water supply is adequate to produce the desired crop yield. Allocation of a deficit water supply to competing fields or irrigators is beyond the scope of this section.

Concepts developed in this part of chapter 2 are provided to explain and illustrate the use of irrigation water requirement information in designing and managing irrigation projects. This is not a design guide for irrigation delivery systems. The material presented is an introduction to complex procedures that are often poorly documented. Refer to other appropriate guidelines for more information on project design.

(b) Irrigation project requirements

Irrigation water requirements can be used to design, manage, and upgrade an irrigation project. The project is defined as blocks of irrigated land that are supplied by a network of canals, pipelines, or both, from a single water source. The irrigated block generally involves several farms with multiple fields per farm. The use of irrigation requirements for designing, managing, and upgrading irrigation projects is similar; thus, general examples are provided to illustrate the procedure.

Irrigation projects must distribute the available water supply to irrigators in an equitable and dependable manner. The irrigator and the water supplier must know what to expect. The only beneficial use of the water diverted into the irrigation project is from the onfarm use of the water for crop production. Thus, it is sensible to provide water to maximize the onfarm benefits. However, there are increasing costs for attaining that last gain of benefits. In some cases the cost of water delivery exceeds the incremental benefit of the improved water supply. Thus, a marginal analysis is necessary to design and operate systems economically. Tradeoffs also exist between the convenience of the supplies versus the flexibility of the irrigator. The issues of economics and flexibility must ultimately be considered in irrigation project operations. These issues will be described through examples of various types of delivery schedules and their impact with respect to onfarm and project management.

(1) Types of delivery schedules

Delivery schedules vary from totally rigid to totally flexible. The rigid schedules are most easily managed by the supplier, while the totally flexible schedules generally produce the highest water use efficiency on the farm if the onfarm irrigation system is well managed.

The *continuous supply system* is the simplest delivery schedule. With this system, a constant flow rate is delivered to the farm turn-out. For a totally continuous system, the supply rate is delivered at a starting time during the season and is shut off at the end of the growing season regardless of the onfarm demand. The supplier can easily manage the system because few decisions are needed and communication between the supplier and the irrigator is not necessary. The constant delivery system generally leads to poor onfarm efficiency because water is supplied when it is not needed and is unavailable in enough quantity during peak use periods. The continuous supply system results in the minimum canal and delivery system capacity. The continuous flow rate is generally quite low and is difficult to manage especially for surface irrigation systems.

A *rotational delivery system* is also a rigid schedule. It supplies a constant discharge (flow rate) to a farm for a fixed duration. The farm then does not receive another supply for a period of time called the irrigation interval. This system does not require communication between the supplier and the farmer and can

result in poor onfarm efficiency because of the variability of the irrigation demand during the growing season. A rotational system has an advantage over a continuous delivery system because the supply rate is large enough to manage and generally requires less labor. A rotational system also allows other field operations to occur more easily than continuous delivery. The capacity of the primary delivery system is generally similar to that of the continuous flow system, but the capacity of the system delivering water to the farm turn-out and the onfarm delivery system generally is larger than that for continuous delivery.

A *demand system*, a flexible schedule, is at the other extreme of the delivery schemes. A pure demand system allows users to remove an unregulated amount of water from the delivery system at the irrigator's convenience. The length, frequency, and rate of water delivery are totally at the irrigator's discretion. A demand system requires the irrigator to communicate with the supplier and generally requires a larger delivery capacity, which increases costs, especially close to the farm. The extra cost of a demand delivery system would hopefully be paid for through improved production on-farm or by irrigating more area with the water saved from increased efficiency.

An *arranged delivery system* varies between the rigid and pure demand schedules. With these supply schedules, either the rate, duration, or frequency, or all three, can be arranged. An agreement is reached between the irrigator and the supplier. Although an arranged schedule provides flexibility to the farmer and generally maximizes water use efficiency, it has some potential problems. First, the manager of the project and the irrigator must understand good water management to manage an unsteady supply system. Second, the equality of water distribution is generally in question and may require investment in special monitoring equipment to measure water consumption. This increases project and production costs. With irrigation projects, especially large projects, the delay between the time an irrigator orders water and when it is delivered is substantial. Because of this, the irrigator should schedule irrigations to determine how much and when water is needed. If climatic conditions change, especially if a substantial rain is received over a large area, during the time between water release and delivery, the efficiency will decrease. This is true, however, of all delivery systems.

The type of delivery system is important in design and management of irrigation projects. Examples in this section help to illustrate the use of irrigation requirements in these activities; however, actual design and management are much more involved than illustrated. The many aspects of project design and management were discussed in a symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers (Zimbelman 1987).

Delivery schedules depend on the delivery system used. The effect of the delivery system on design will be discussed using the procedures described by Clemmens (1987). Clemmens indicated that three factors are important in sizing the delivery system: delivery flow rate, delivery duration, and the peak water requirement or irrigation frequency. In this context, the peak water requirement represents a gross irrigation capacity requirement. Two peak requirements are important. The first is the aggregate peak during the season when considering all crops and fields within an irrigated block or project. The second is the peak water requirement during the season of any crop on a segment of the delivery system.

The average peak is used to size large canals and the upper end of the supply system because there is little likelihood that the entire area will be planted to the crop with the maximum peak capacity requirement. However, at the end of the canal, the maximum capacity may be needed because the high demand crop could be a principal part of the service area. The average application efficiency during the peak use period should be used to compute the water requirement.

Clemmens indicates that many systems are designed assuming a normal flow rate called the "delivery flow rate." The delivery flow rate might vary from 1 to 3.5 cubic feet per second for a graded surface, trickle or sprinkler irrigation system, and as high as 35 cubic feet per second on a large, level-basin system. The delivery flow rate is easy to manage because the supplier and irrigator know the supply rate, which is generally constant.

The area that can be irrigated with the delivery flow rate is:

$$A_t = 448.8 \frac{\left(Q_t H_r\right)}{24\ W_u} \qquad [2–112]$$

where:
A_t = the irrigated area (acres)
Q_t = the delivery flow rate (ft^3/s)
H_r = the daily delivery period (hr/d of water delivery)
W_u = the average peak water use rate (gpm/acre)

A_t is the area that can be irrigated using a continuous water supply or a complete rotation system. Clemmens (1987) called A_t the rotational area. The rotational area is computed in example 2–38 for a hypothetical project in Colorado.

The area, flow rate, duration, and gross irrigation depth are related by:

$$t_i = \frac{\left(A_i\ F_g\right)}{\left(23.8\ Q\right)} \qquad [2–113]$$

where:
t_i = the duration of an individual irrigation (days)
A_i = irrigated area (acres)
F_g = gross irrigation depth (inches)
Q = system flow rate (ft^3/s)

The gross irrigation depth can be determined by management preference. With trickle and some sprinkler and level basins, the depth of water applied may be less than required to refill the crop root zone. For other systems the depth equals the soil water depletion divided by the application efficiency.

The minimum irrigation depth that will satisfy crop needs occurs for the continuous supply system where water is supplied for the entire time between irrigations. The frequency (f) of an irrigation is the reciprocal of the time interval between irrigations. For example, if a field is irrigated once every 10 days, the

Example 2–38 Continuous delivery system

Given: A project is to irrigate corn in southeast Colorado using a furrow irrigation system that is 80 percent efficient. The soil is a silt loam that has available water holding capacity of 2.0 inches per foot of soil. The root depth during the peak use period is 4 feet, and the management allowable depletion has been determined to be 50 percent. The delivery flow rate is 4.1 cubic feet per second, and water is delivered 24 hours a day.

Find: Compute the rotational area for this system.

Solution:

1. Use figure 2–57 with 95 percent probability to compute the net capacity:
   Allowable depletion = 0.5 x 4 ft x 2 in/ft = 4 inches
   From figure 2–57, the net system capacity needed is 0.21 in/d
   Using equation 2–107 the average peak water use rate is:

$$W_u = 18.86 \times \frac{C_n}{E_a}$$
$$= 18.86 \times \frac{0.21\ \text{in / d}}{0.80}$$
$$= 5.0\ \text{gpm / ac}$$

2. Using equation 2–112, the rotational area is then:

$$A_t = \frac{448.8 \times 4.1 \times 24\ \text{hr / d}}{5.0\ \text{gpm / ac} \times 24}$$
$$= 370\ \text{ac}$$

frequency is 0.1 days^{-1}. The irrigation frequency can be computed by:

$$f = \frac{W_u}{\left(18.86\ F_g\right)} \qquad [2–114]$$

where:
f = irrigation frequency (days^{-1})
W_u = average peak water use rate (gpm/acre)
F_g = the gross irrigation depth (inches)

With a continuous supply, the duration equals the reciprocal of the frequency, and small parts of the field are irrigated continuously during the irrigation interval. This system is generally inefficient and requires an excessive amount of labor. The minimum frequency occurs where the gross depth equals the allowable depletion. A smaller frequency, or longer interval, would result in crop water stress between irrigations.

A rotational system was developed to better manage large-scale delivery systems. Using this system, the irrigated area is subdivided and the delivery flow rate is supplied to each subdivision, or irrigated block, for a specified duration once during the irrigation interval. A delivery schedule for a rotational system is illustrated in example 2–39.

Examples 2–38 and 2–39 illustrate that the required capacity for the 370 acre area will be 4.1 cubic feet per second for either the continuous or the rotational delivery system. The difference between the supply strategies comes in the size of the supply system needed to irrigate each 37 acre block. For the continuous system, a tenth of the delivery flow rate (0.41 ft^3/s) was supplied. With rotational delivery, each supply system must have enough capacity to carry the delivery flow rate (4.1 ft^3/s) for 1 day and then will be dry for 9 days.

Example 2–39 Rotational delivery system

Given: Use the information from the example 2–38 and assume that the project is divided into 10 irrigated blocks of 37 acres each.

Find: The supply capacity for each block and the duration of irrigation.

Solution:

1. With 10 blocks, a frequency of 0.1 days^{-1} could be used, thus each block would be irrigated for a duration of 1 day. The gross irrigation would be determined from equation 2–114 as:

$$F_g = \frac{W_u}{\left(18.86 \times f\right)} = \frac{5.0\ \text{gpm / ac}}{\left(18.86 \times 0.1\ \text{day}^{-1}\right)}$$

$$F_g = 2.65\ \text{in}$$

Since the allowable depletion is 4 inches for this system, this depth is acceptable.

2. With a duration of 1 day, the flow rate to each block is determined from equation 2–113:

$$Q = \frac{A_i \times F_g}{\left(23.8 \times t_i\right)} = \frac{37\ \text{ac} \times 2.65\ \text{in}}{\left(23.8 \times 1\ \text{day}\right)}$$

$$Q = 4.1\ \text{ft}^3\ /\ \text{s}$$

The needed flow rate is exactly the same as that for continuous supply because no down time or flexibility is designed into the system.

Suppose that a demand system were implemented. If the goal was to supply the water to a block during 1 day (same duration as for the rotational system), the maximum demand would occur where each block ordered the delivery flow rate on the same day. Thus, the supply system to the 370 acre area must be 10 times the capacity of either the continuous or the rotational delivery system. The supply capacity to each block would still need to be 4 cubic feet per second. Obviously, the cost of the demand system would be much higher than that for the continuous system.

Various authors in the proceedings edited by Zimbelman (1987) point out that the effect of a demand schedule is most severe near farm turn-outs and that the impact on major supply canals and pipelines is reduced because it is unlikely that all users on a project will need a full delivery flow rate at the same time. Pure demand systems are rare, especially for surface irrigation projects where the delivery flow rate is large. This type system is difficult for the supplier to manage and generally is expensive to build.

An example of an arranged delivery system would be to require a 2-day duration with a maximum of 5 blocks irrigated at anytime. The irrigator would need to place a water order in advance to allow time for the supplier to provide the supply. The supplier might allow a maximum flow rate of 2 cubic feet per second per block. The irrigator could request any flow rate up to 2 cubic feet per second and could request more than one supply during a 10-day period.

Many other examples could be developed that allow a range of duration, frequency, and flow rate. The supplier and irrigator should be considered in design and cooperate in operation of an arranged system. In some cases suppliers have attempted to schedule irrigations for the district and provide water based on that schedule. Such systems have had limited success because farmers are unwilling to relinquish control of irrigation management.

Arranged delivery schedules generally are more complicated because the probability of various demands is needed to size the system and to manage the system once a project in on-line. Clemmens (1986) showed that the flexibility allowed by arranged schedules causes the capacity needed in an irrigation project to be bigger than that for rotational systems at the farm turn-out level, but that there was less effect upstream.

(2) Sizing delivery systems

Examples 2–38 and 2–39 illustrate the interaction of rate, duration, and frequency and the effect of the type of delivery system on the capacity needed in an irrigation project. The examples are overly simplistic and do not demonstrate the actual procedure used to size delivery systems.

The procedure used by the U.S. Bureau of Reclamation to size delivery systems is illustrated in figure 2–63. The process begins by determining the net irrigation water requirement using the procedures as described in section 623.0210. For a farm, the part of the irrigable area that will be irrigated should be determined. A commonly used value for U.S. Bureau of Reclamation projects is 97 percent. The onfarm irrigation efficiency should be determined using procedures from section 623.0209. The duration for delivery to the farm should then be determined to provide an estimate of the amount of time irrigation water will be provided to the farm turn-out. Finally, water demands for any beneficial uses besides evapotranspiration should be determined. Given this information, the farm delivery requirement is determined. The delivery schedule should include the necessary capacity, duration, and frequency for all farms served by each component of the delivery system.

The U.S. Bureau of Reclamation uses a flexibility factor to account for the type and management of the delivery system. The factor is the ratio of the actual delivery compared to the minimum delivery if the system operated continuously. Thus a flexibility factor of 1.2 provides 20 percent more capacity than would be needed if the canal supplied water continuously. A flexibility factor of 1.2 allows irrigation 83 percent of the time and still meets the peak water requirements. Of course, the larger the flexibility factor, the higher the cost of the project. The flexibility factor generally is more than 1.0 to provide excess capacity so that irrigators can better manage water on the individual farms. Also, it is generally larger when the area served by a delivery system is small. Selection of a flexibility factor is primarily based on judgment of the designer.

The flexibility factor and the farm delivery requirements are used to develop a system capacity curve as shown in figure 2–64. The system capacity curve relates area in a subdivision of the project to the supply needed for that block. For example, suppose a design following procedures in section 623.0210 called

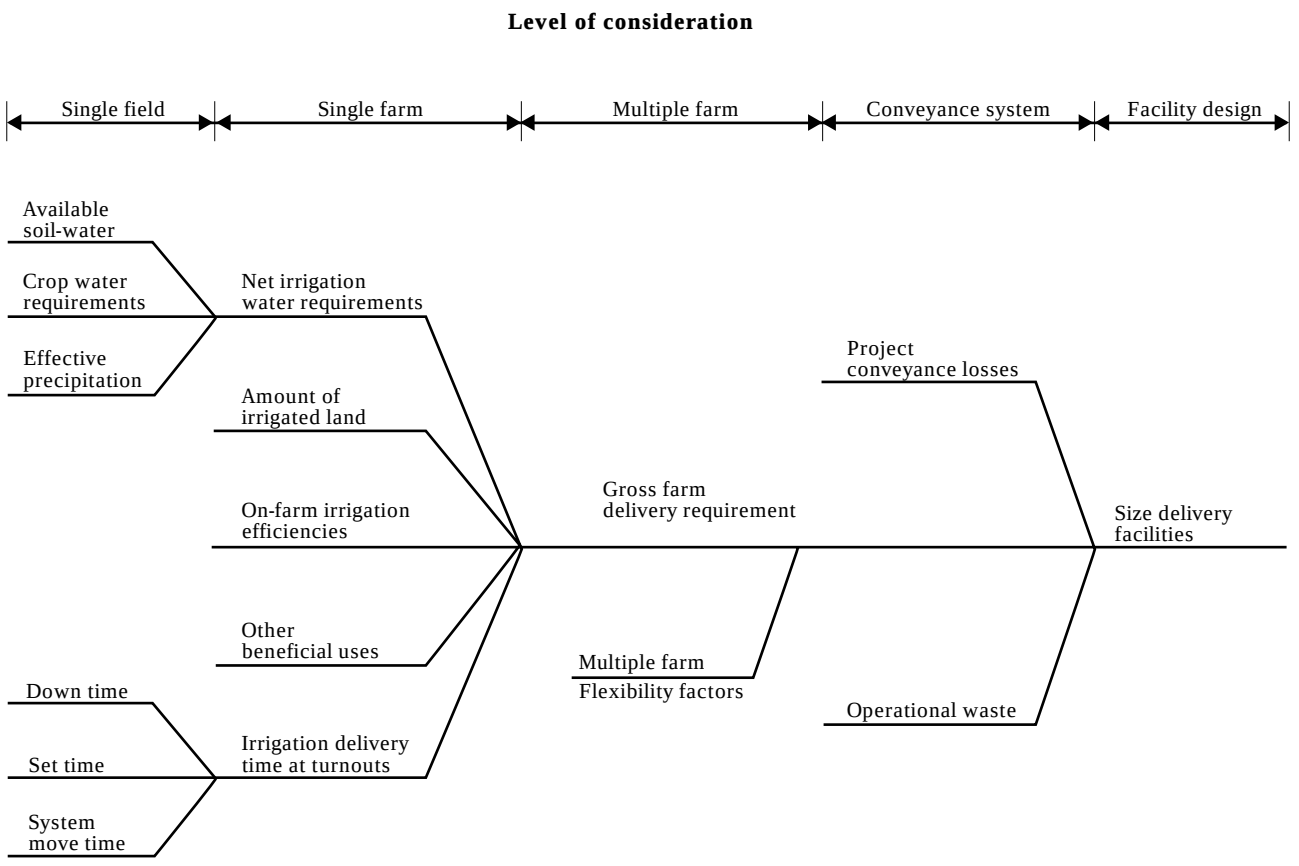
for delivery of 6.9 gpm/acre to the farm. If a flexibility factor of 1.2 is used, the canal capacity would need to be 8.3 gpm/acre. Often the delivery is measured in cubic feet per second. Because 1.0 ft^3/s = 448.8 gpm, 1 cubic foot per second would be adequate to irrigate about 54 acres (i.e., 54 acres x 8.3 gpm/acre = 448 gpm = 1 ft^3/s). This ratio is then used as in figure 2–64 for the curve for turnouts and small laterals. If the area served were 10,000 acres, the delivery into the small laterals would need to be:

$$\frac{10{,}000 \text{ acres}}{54 \text{ acres per ft}^3 / \text{s}} = 185 \text{ ft}^3 / \text{s}$$

After the system capacity curve is determined, the conveyance losses and operational waste can be estimated. Information from similar systems in the same location can be used along with the data presented in section 623.0209 to develop initial planning estimates of conveyance and operational losses. Estimates for design and operation should be based on the best possible local information. Field investigations must be conducted to ensure that the selected values are appropriate. With the overall conveyance efficiency determined, delivery capacity needed for a section of the project will be known. The design of the project thus begins at the farm and progresses upstream to the water source.

An example solution for sizing a lateral supply canal is summarized in table 2–57 for the system shown in figure 2–65. It is assumed in table 2–57 that an appropriate analysis using procedures through section 623.0210 has been conducted to determine the net system capacity for each crop and the net capacity during the peak use period for the farm. Using these

Figure 2–63 Processes involved in sizing irrigation projects (adapted from Gibbs 1972)



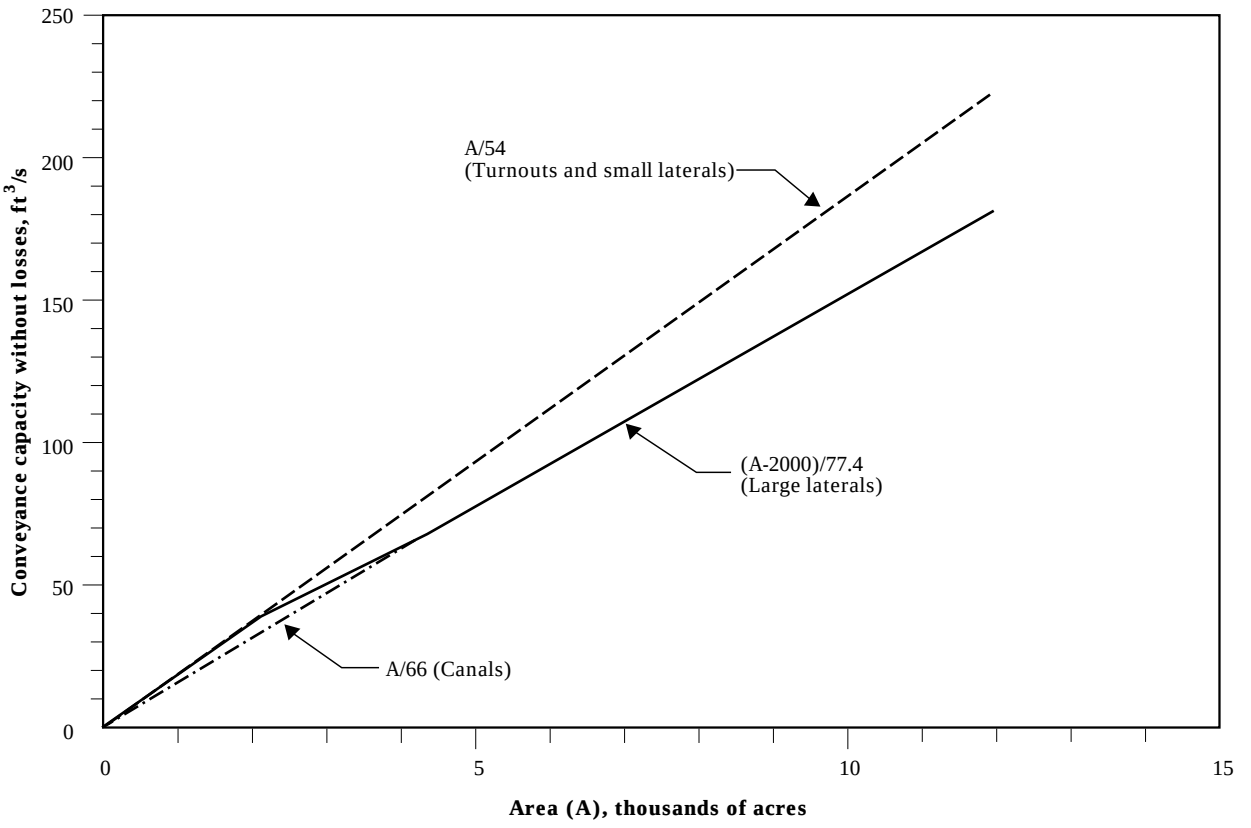
data, the delivery capacity needed for continuous supply at the field is computed using the field application efficiency and the water use rate during the peak period. The continuous delivery flow rate is determined by solving for Q_t in equation 2–112.

The conveyance efficiency for each field is computed as the product of the efficiency of the series of distribution systems that supply each field. For example, with field 1, the field conveyance efficiency is the product of the conveyance efficiency of canals 1 and 2 (0.9 x 0.8 = 0.72, or 72%). If water were supplied continuously to field 1, the capacity would have to be 1.64 ÷ 0.72 = 2.28 ft^3/s. Using a flexibility factor of 1.2 would increase the supply capacity needed for field 1 to 2.28 x 1.2 = 2.73 ft^3/s.

When the continuous farm delivery requirement is added for all fields, the farm requirement is about 19.5 ft^3/s. Thus, about 47 acres can be irrigated with 1 ft^3/s for this farm. Using the flexibility factor of 1.2 increases the farm requirement to about 23.4 ft^3/s and reduces the area per cubic foot per second ratio to 39.3 acres per cubic foot per second.

The capacity of the lateral canal can be determined using the area per cubic foot per second ratio determined for the representative farm. There are 5,000 acres in the irrigated block, and the lateral canal efficiency is expected to be about 90 percent. Therefore, the lateral canal will need a capacity of about 141 ft^3/s (i.e., 5,000 acres ÷ 39.3 acres per ft^3/s ÷ 0.9).

Figure 2–64 System capacity curve for a conveyance system (adapted from Gibbs 1972)



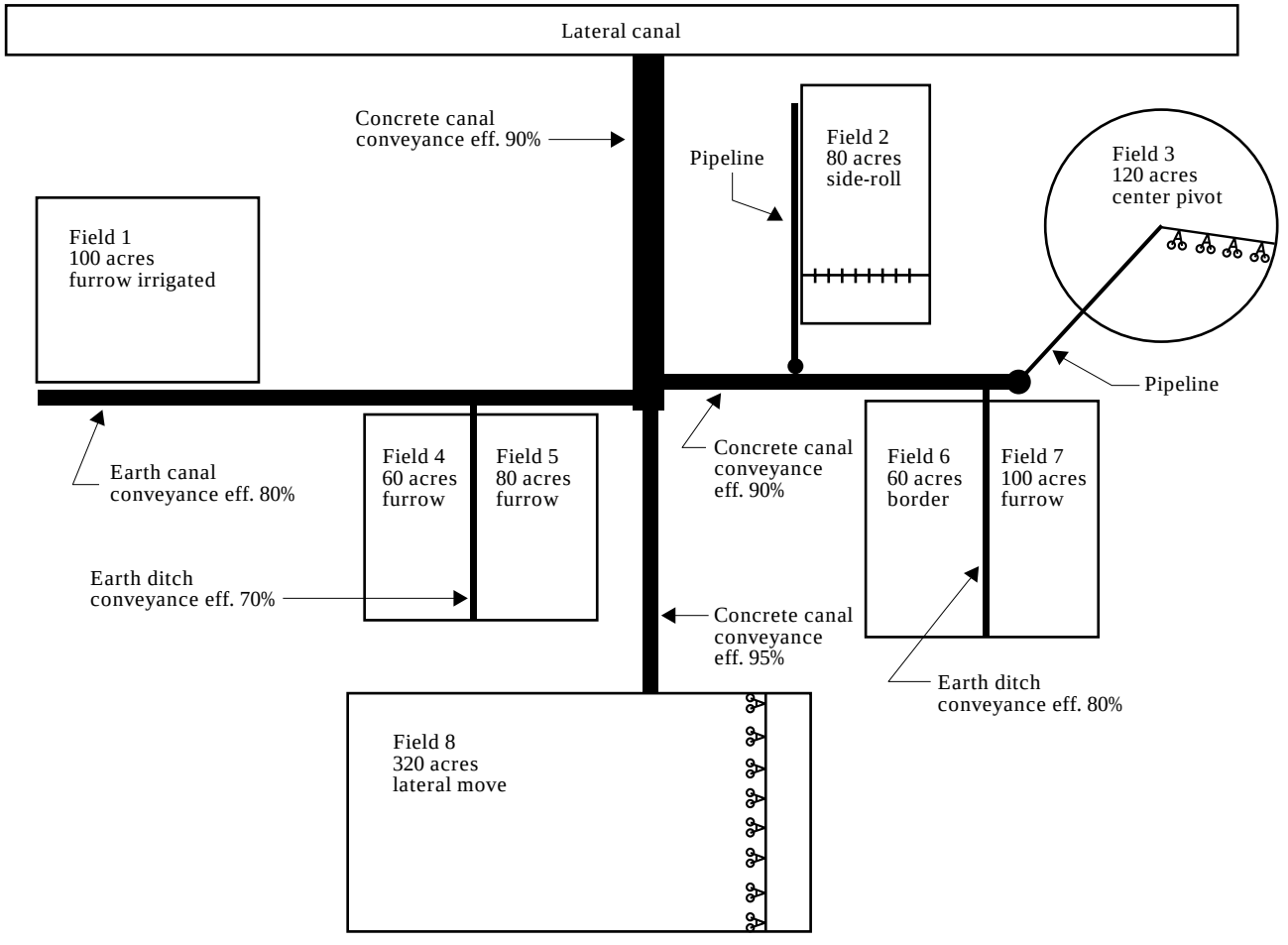
A system capacity curve similar to the one shown in figure 2–64 can be used to determine the capacity needed for similar blocks on a project and is essentially what was done for the sizing example in table 2–57.

(c) Onfarm delivery schedules

Two types of onfarm delivery schedules are necessary for irrigation projects. The first is needed to design the supply system for the farm and will be based on the expected supply needed for individual fields. A well-developed supply schedule provides useful information where the project is new and the irrigator lacks experience. The initial farm delivery schedule depends on the design flow rate and duration and frequency of irrigation for each field. Other chapters of part 623 of the USDA-SCS National Engineering Handbook discuss design of irrigation systems for specific conditions, thus a detailed example of the design for an individual field will not be included here. It must be emphasized that the individual field design must be compatible with the farm and district supply schedules.

The flow rate frequency and duration of supply must be determined for each field and combined to determine the capacity needed for each supply section. The peak water requirement for a specific field may not

Figure 2–65 Delivery system layout for a farm served by a large lateral canal



occur at the same time of the season as the farm or project peak. The irrigation requirement for each field along a supply system should be considered throughout the season to select the peak supply capacity of a specific reach of the delivery system.

The farm depicted in figure 2–65 and table 2–57 illustrates several problems that can be encountered when developing delivery schedules for heterogeneous fields. The farm will be difficult to manage for a rotational supply schedule. Sprinkler systems are generally most efficient for small, frequent irrigations, whereas surface irrigation usually requires a larger flow rate and less frequent irrigation. Finding a farm supply schedule to facilitate efficient irrigation on all fields and still fit the project delivery schedule can be quite involved. Auxiliary storage of water on the farm may be necessary if the supply duration to the farm is too short for the sprinkler systems to irrigate the entire field.

The second onfarm supply schedule is the real-time schedule for the farm. The actual conditions on the farm when scheduling irrigation will not be the same as those when the system was designed. The irrigation manager must develop a new onfarm schedule for each irrigation. This is especially critical if water is provided by an arranged delivery system.

Buchleiter and Heermann (1987) detail the use of irrigation scheduling procedures to manage a large, multifield farm. These scheduling functions involve many decisions and constraints that must be considered to develop an effective and feasible schedule. Others have developed routines to provide a water delivery schedule to optimize labor use on the farm (Trava, et al. 1977 and Pleban, et al. 1983). These techniques are beyond the scope of this chapter, but illustrate the use of irrigation water requirements in sophisticated management of modern irrigation systems. Several articles also discuss automation of irrigation projects (Zimbelman 1987). Accurate irrigation water requirement information is the foundation that supports automation.

Table 2–57 Example of canal sizing problem for the system shown in figure 2–65

Field	Crop	Productive area	Applic. effic.	- - - - Net system capacity - - - Peak crop	Use during month of farm peak		Gross continuous delivery flow rate	Conveyance efficiency field delivery systems	Continuous farm delivery required	Capacity for a 1.2 flexibility factor
		(acres)	(%)	(gpm/ac)	(gpm/ac)	(in/d)	(ft^3/s)	(%)	(ft^3/s)	(ft^3/s)
1	Corn	100	75	5.5	5.5	0.29	1.64	72	2.28	2.73
2	Alfalfa	80	80	7.0	7.0	0.37	1.56	90	1.73	2.08
3	Corn	120	80	6.0	6.0	0.32	2.00	90	2.22	2.67
4	Grain sorghum	60	65	5.0	4.5	0.26	0.92	63	1.46	1.75
5	Soybeans	80	65	5.2	4.7	0.28	1.29	63	2.05	2.46
6	Alfalfa	60	75	6.5	6.5	0.34	1.16	72	1.61	1.93
7	Corn	100	70	5.2	5.2	0.28	1.66	72	2.31	2.77
8	Corn	320	85	6.0	6.0	0.32	5.04	86	5.86	7.03
	Total	920							19.5	23.4

Farm requirement = 47.1 acres per ft^3/s
Flexibility factor = 1.2
Slope of conveyance capacity curve = 39.3 acres per ft^3/s
Area served by lateral canal = 5,000 acres
Overall conveyance efficiency of lateral = 90%
Lateral canal capacity needed = 141 ft^3/s

(d) Water conservation

Irrigated agriculture consumes the majority of the water used in the western United States. In many areas water shortages are developing, and competition for water is increasing. Some people view water conservation in irrigated agriculture as one means to alleviate competition; however, conservation is poorly understood and difficult to define.

The Council for Agricultural Science and Technology (CAST 1988) used an annual water balance to illustrate the problem of defining conservation. In the annual balance the sources of water are precipitation, applied irrigation water, and stored soil water. Conservation means reducing these amounts of water. The amount of precipitation received cannot be controlled. Likewise, the amount of water in the soil can only be used one time, and over long periods stored soil moisture is a small part of the supply. Thus, the amount of irrigation water, which comes from either ground or surface water supplies, must be reduced to conserve water.

Irrigation water can result in transpiration, evaporation, leaching of salts, deep percolation beyond the leaching requirement, and surface runoff. If less water is applied, then one of the five forms of water use must also decrease. Except for phreatophytes along delivery systems, reductions in transpiration and leaching generally result in less income from crop yield. In many cases the reduction in yield costs more than the water is worth. Conservation in this manner is economically unsound.

Reduction of evaporation through improved application, storage, and conveyance systems may truly conserve water. Methods to cover or shade the soil to absorb radiant energy and to reduce water conductance through the soil can contribute to water conservation. In some systems the savings of evaporation may be small or uncontrollable. Runoff and deep percolation in excess of leaching needs are often viewed as wasteful.

The Council for Agricultural Science and Technology points out that runoff and deep percolation may be lost for an individual farm use, but some of each quantity may return to the water supply by either return flow to a river or as recharge to an aquifer (CAST 1988). Water that returns to the water supply is available to be used again by the same or an alternate user. However, some runoff and deep percolation accumulate in locations where reuse is impossible or at least economically or environmentally infeasible. Runoff and deep percolation that cannot be reused should be considered a loss that could potentially be conserved.

Conservation of irrigation water raises several political and legal questions, as well. In some cases conservation may not be feasible because those that benefit may not be the ones paying for conservation. For example, an upstream irrigator might be able to improve his system to reduce the amount of water diverted to his farm. That would provide more water downstream for other users; however, the upstream farmer would not benefit. Obviously, the upstream farmer will be hard to persuade to pay for that practice.

Even though water conservation is difficult to define and measure, efforts to use less water for irrigation will more than likely increase. Where conservation is considered, an evaluation of the irrigation project should be made to determine the potential benefits. The procedure developed by Hedlund and Koluvek (1985) is helpful in inventorying potential impacts from building a new project or for renovating an existing project. The summary form for their analysis procedure is shown in figure 2–66. Their procedure has been incorporated into the Farm Irrigation Rating Index by the SCS (USDA 1991).

Water conservation will require that all aspects of irrigated agriculture be evaluated. Alternate cropping and tillage systems and other changes can contribute to water conservation in irrigated agriculture. Methods developed in this chapter are helpful in quantifying water use and conservation potential for some changes. However, several important processes needed to fully describe the effect of differing practices on water conservation are not adequately presented by the methods in this chapter. Future research and developments are needed to completely describe the effect of design and management on the fate of the applied irrigation water.

Figure 2–66 An evaluation form for water conservation inventories of irrigation systems (from Hedlund and Koluvek 1985)

State: Water district: Ditch system:

Watershed: Irrigated area, acres: No. of farms:

Factors	Rating low-high	Score	High	Moderate	Low
			Circle the criteria approximating the level; if appropriate		
Water Quantity					
1. Ground water mining	0-5		100%	50%	None
2. Increase farm water supply	0-4		Develop surpluses	Eliminate shortages	No change
3. Reduce diversions	0-4		>50%	10-50%	<10%
4. Reduce return flow	0-3		>50%	10-50%	<10%
5. Improve efficiency					
a. Conveyance	0-2		>30%	10-30%	<10%
b. Onfarm	0-2		>20%	5-20%	<5%
Subtotal	20		Effects:		
Economics					
1. Sustain viable community	0-5		Depressed area	Some potential	Viable economy
2. Decrease in cost to produce	0-4		significant	some potential	No potential
3. Increase in gross value	0-4		>$150 gross/acre	50-100 gross $/acre	<50 gross $/acre
4. Increase productivity					
a. Water shortage	0-2		treatable (optimum)	Some yield increase	No potential
b. Soil salinity	0-2		treatable (optimum)	Some yield increase	No potential
c. Water logging	0-2		treatable (optimum)	Some yield increase	No potential
5. Sale of conserved water	0-1		Easily sold >$100/ac-ft	No sale, but used	No sale, surplus
Subtotal	20		Effects:		
Environmental					
1. Water quality					
a. Salinity	0-2		Treatable (significant)	Some potential	No potential
b. Sediment	0-2		Treatable (significant)	Some potential	No potential
c. Nutrient & pesticides	0-2		Treatable (significant)	Some potential	No potential
2. Wetlands—wildlife	0-2		Few effects	Some change	Lost habitat
3. Instream flow	0-2		Significant improvement	No change	Reduced flow
4. Erosion	0-2		>5 ton/acre reduction	1-5 ton/acre	1 ton/acre
5. Environmental impacts	0-3		None identified	Some	Controversial
Subtotal	15		Effects:		
Social effects					
1. Energy use	0-4		Savings	No change	Increase use
2. Indian lands	0-4		All Indian	Affects Indian	None
3. Loss of prime land	0-4		High value	Low value	No change
4. Impact on existing users	0-2		Change to high value	Some improvement	No impact
5. Life, health, safety	0-1		Reduces hazard	Some improvement	No impact
Subtotal	15		Effects:		
Legal and institutional					
1. Advocate of beneficial use, conservation, salvage	0-4		No conflicts	Neutral	Many problems
2. Ground/surface water laws	0-2		Strong law	Neutral	No laws
3. Loss of water to other users	0-1		No conflict	Neutral	Problems
4. Windfall benefits	0-1		<$50,000/farmer	Some over $50,000	Over 100,000
5. New land	0-2		No new land	Very little	>20% new land
Subtotal	10		Effects:		
Implemental Potential					
1. Acceptability					
a. Local	0-4		Active support	Supportable	Opposition
b. State	0-3		Active support	Supportable	Opposition
c. National program	0-2		Fits USDA program	Supportable	Requires new
2. Technical assistance	0-2		<4 man-years	4-10 man-years	>10 man-years
3. Capital cost					
a. Conveyance	0-2		<$250/acre	250-1000 $/acre	>1000 $/acre
b. Onfarm	0-3		<$250/acre	250-800 $/acre	>800 $/acre
4. Financial incentives	0-2		<$1 million	1-10 million	>$10 million
5. Time to plan and design	0-2		<1 year	1-5 years	>5 years
Subtotal	20		Effects:		
Total		(100 points possible)		Bonus Points:	

Magnitude of problem:

Viable solutions:

Additional impacts:

Appendix A Blaney-Criddle Formula (SCS Technical Release No. 21)

Because of the historical and in some cases legal significance of the Blaney-Criddle equation described in Technical Release No. 21 (SCS 1970), that method is presented in this appendix. The following material is taken directly from Technical Release No. 21. The reference crop methods presented in sections 623.0203 and 623.0204 have proven to be more accurate than this version of the Blaney-Criddle formula. Thus, the reference crop and appropriate crop coefficient techniques are recommended.

Disregarding many influencing factors, consumptive use varies with the temperature, length of day, and available moisture regardless of its source (precipitation, irrigation water, or natural ground water). Multiplying the mean monthly temperature (t) by the possible monthly percentage of daytime hours of the year (p) gives a monthly consumptive-use factor (f). It is assumed that crop consumptive use varies directly with this factor when an ample water supply is available. Expressed mathematically,

$$u = kf$$
$$U = \text{sum of } kf = KF$$

where:

U = Consumptive use of the crop in inches for the growing season.

K = Empirical consumptive-use crop coefficient for the growing season. This coefficient varies with the different crops being irrigated.

F = Sum of the monthly consumptive-use factors for the growing season (sum of the products of mean monthly temperature and monthly percentage of daylight hours of the year).

u = Monthly consumptive use of the crop in inches.

k = Empirical consumptive-use crop coefficient for a month (also varies by crops).

f = Monthly consumptive-use factor (product of mean monthly temperature and monthly percentage of daylight hours of the year).

$$f = \frac{t \times p}{100}$$

where:

t = Mean monthly air temperature in degrees Fahrenheit.

p = Monthly percentage of annual daylight hours. Values of p for 0 to 65 degrees north latitude are shown in table 2A–1.

Note: Value of t, p, f, and k can also be made to apply to periods of less than a month.

Following are modifications made in the original formula:

$$k = k_t \times k_c$$

where:

k = a climatic coefficient which is related to the mean air temperature (t),

k_t = .0173t - .314. Values of k_t for mean air temperatures from 36 to 100 degrees are shown in table 2A–4.

k_c = A coefficient reflecting the growth stage of the crop. Values are obtained from crop growth stage coefficient curves as shown in figures 2A–1 through 2A–25 at the back of this appendix.

The consumptive-use factor (F) may be computed for areas for which monthly temperature records are available, if the percentage of hours that is shown in table 2A–1 is used. Then the total crop consumptive use (U) is obtained by multiplying F by the empirical consumptive-use crop coefficient (K). This relationship allows the computation of seasonal consumptive use at any location for those crops for which values of K have been experimentally established or can be estimated.

Table 2A–1 Monthly percentage of daytime hours (p) of the year for northern latitudes

Latitude N	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
65°	3.52	5.13	7.96	9.97	12.72	14.15	13.59	11.18	8.55	6.53	4.08	2.62
64°	3.81	5.27	8.00	9.92	12.50	13.63	13.26	11.08	8.56	6.63	4.32	3.02
63°	4.07	5.39	8.04	9.86	12.29	13.24	12.97	10.97	8.56	6.73	4.52	3.36
62°	4.31	5.49	8.07	9.80	12.11	12.92	12.73	10.87	8.55	6.80	4.70	3.65
61°	4.51	5.58	8.09	9.74	11.94	12.66	12.51	10.77	8.55	6.88	4.86	3.91
60°	4.70	5.67	8.11	9.69	11.78	12.41	12.31	10.68	8.54	6.95	5.02	4.14
59°	4.86	5.76	8.13	9.64	11.64	12.19	12.13	10.60	8.53	7.00	5.17	4.35
58°	5.02	5.84	8.14	9.59	11.50	12.00	11.96	10.52	8.53	7.06	5.30	4.54
57°	5.17	5.91	8.15	9.53	11.38	11.83	11.81	10.44	8.52	7.13	5.42	4.71
56°	5.31	5.98	8.17	9.48	11.26	11.68	11.67	10.36	8.52	7.18	5.52	4.87
55°	5.44	6.04	8.18	9.44	11.15	11.53	11.54	10.29	8.51	7.23	5.63	5.02
54°	5.56	6.10	8.19	9.40	11.04	11.39	11.42	10.22	8.50	7.28	5.74	5.16
53°	5.68	6.16	8.20	9.36	10.94	11.26	11.30	10.16	8.49	7.32	5.83	5.30
52°	5.79	6.22	8.21	9.32	10.85	11.14	11.19	10.10	8.48	7.36	5.92	5.42
51°	5.89	6.27	8.23	9.28	10.76	11.02	11.09	10.05	8.47	7.40	6.00	5.54
50°	5.99	6.32	8.24	9.24	10.68	10.92	10.99	9.99	8.46	7.44	6.08	5.65
49°	6.08	6.36	8.25	9.20	10.60	10.82	10.90	9.94	8.46	7.48	6.16	5.75
48°	6.17	6.41	8.26	9.17	10.52	10.72	10.81	9.89	8.45	7.51	6.24	5.85
47°	6.25	6.45	8.27	9.14	10.45	10.63	10.73	9.84	8.44	7.54	6.31	5.95
46°	6.33	6.50	8.28	9.11	10.38	10.53	10.65	9.79	8.43	7.58	6.37	6.05
45°	6.40	6.54	8.29	9.08	10.31	10.46	10.57	9.75	8.42	7.61	6.43	6.14
44°	6.48	6.57	8.29	9.05	10.25	10.39	10.49	9.71	8.41	7.64	6.50	6.22
43°	6.55	6.61	8.30	9.02	10.19	10.31	10.42	9.66	8.40	7.67	6.56	6.31
42°	6.61	6.65	8.30	8.99	10.13	10.24	10.35	9.62	8.40	7.70	6.62	6.39
41°	6.68	6.68	8.31	8.96	10.07	10.16	10.29	9.59	8.39	7.72	6.68	6.47
40°	6.75	6.72	8.32	8.93	10.01	10.09	10.22	9.55	8.39	7.75	6.73	6.54
39°	6.81	6.75	8.33	8.91	9.95	10.03	10.16	9.51	8.38	7.78	6.78	6.61
38°	6.87	6.79	8.33	8.89	9.90	9.96	10.11	9.47	8.37	7.80	6.83	6.68
37°	6.92	6.82	8.34	8.87	9.85	9.89	10.05	9.44	8.37	7.83	6.88	6.74
36°	6.98	6.85	8.35	8.85	9.80	9.82	9.99	9.41	8.36	7.85	6.93	6.81
35°	7.04	6.88	8.35	8.82	9.76	9.76	9.93	9.37	8.36	7.88	6.98	6.87
34°	7.10	6.91	8.35	8.80	9.71	9.71	9.88	9.34	8.35	7.90	7.02	6.93
33°	7.15	6.94	8.36	8.77	9.67	9.65	9.83	9.31	8.35	7.92	7.06	6.99
32°	7.20	6.97	8.36	8.75	9.62	9.60	9.77	9.28	8.34	7.95	7.11	7.05
31°	7.25	6.99	8.36	8.73	9.58	9.55	9.72	9.24	8.34	7.97	7.16	7.11
30°	7.31	7.02	8.37	8.71	9.54	9.49	9.67	9.21	8.33	7.99	7.20	7.16
29°	7.35	7.05	8.37	8.69	9.50	9.44	9.62	9.19	8.33	8.00	7.24	7.22
28°	7.40	7.07	8.37	8.67	9.46	9.39	9.58	9.17	8.32	8.02	7.28	7.27
27°	7.44	7.10	8.38	8.66	9.41	9.34	9.53	9.14	8.32	8.04	7.32	7.32
26°	7.49	7.12	8.38	8.64	9.37	9.29	9.49	9.11	8.32	8.06	7.36	7.37
25°	7.54	7.14	8.39	8.62	9.33	9.24	9.45	9.08	8.31	8.08	7.40	7.42
24°	7.58	7.16	8.39	8.60	9.30	9.19	9.40	9.06	8.31	8.10	7.44	7.47
23°	7.62	7.19	8.40	8.58	9.26	9.15	9.36	9.04	8.30	8.12	7.47	7.51
22°	7.67	7.21	8.40	8.56	9.22	9.11	9.32	9.01	8.30	8.13	7.51	7.56
21°	7.71	7.24	8.41	8.55	9.18	9.06	9.28	8.98	8.29	8.15	7.55	7.60

Table 2A–1 Monthly percentage of daytime hours (p) of the year for northern latitudes—Continued

Latitude N	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
20°	7.75	7.26	8.41	8.53	9.15	9.02	9.24	8.95	8.29	8.17	7.58	7.65
19°	7.79	7.28	8.41	8.51	9.12	8.97	9.20	8.93	8.29	8.19	7.61	7.70
18°	7.83	7.31	8.41	8.50	9.08	8.93	9.16	8.90	8.29	8.20	7.65	7.74
17°	7.87	7.33	8.42	8.48	9.04	8.89	9.12	8.88	8.28	8.22	7.68	7.79
16°	7.91	7.35	8.42	8.47	9.01	8.85	9.08	8.85	8.28	8.23	7.72	7.83
15°	7.94	7.37	8.43	8.45	8.98	8.81	9.04	8.83	8.27	8.25	7.75	7.88
14°	7.98	7.39	8.43	8.43	8.94	8.77	9.00	8.80	8.27	8.27	7.79	7.93
13°	8.02	7.41	8.43	8.42	8.91	8.73	8.96	8.78	8.26	8.29	7.82	7.97
12°	8.06	7.43	8.44	8.40	8.87	8.69	8.92	8.76	8.26	8.31	7.85	8.01
11°	8.10	7.45	8.44	8.39	8.84	8.65	8.88	8.73	8.26	8.33	7.88	8.05
10°	8.14	7.47	8.45	8.37	8.81	8.61	8.85	8.71	8.25	8.34	7.91	8.09
9°	8.18	7.49	8.45	8.35	8.77	8.57	8.81	8.68	8.25	8.36	7.95	8.14
8°	8.21	7.51	8.45	8.34	8.74	8.53	8.78	8.66	8.25	8.37	7.98	8.18
7°	8.25	7.53	8.46	8.32	8.71	8.49	8.74	8.64	8.25	8.38	8.01	8.22
6°	8.28	7.55	8.46	8.31	8.68	8.45	8.71	8.62	8.24	8.40	8.04	8.26
5°	8.32	7.57	8.47	8.29	8.65	8.41	8.67	8.60	8.24	8.41	8.07	8.30
4°	8.36	7.59	8.47	8.28	8.62	8.37	8.64	8.57	8.23	8.43	8.10	8.34
3°	8.40	7.61	8.48	8.26	8.58	8.33	8.60	8.55	8.23	8.45	8.13	8.38
2°	8.43	7.63	8.49	8.25	8.55	8.29	8.57	8.53	8.22	8.46	8.16	8.42
1°	8.47	7.65	8.49	8.23	8.52	8.25	8.53	8.51	8.22	8.48	8.19	8.45
0°	8.50	7.67	8.49	8.22	8.49	8.22	8.50	8.49	8.21	8.49	8.22	8.50

Seasonal consumptive-use coefficients

Consumptive-use coefficients (K) have been determined experimentally at numerous localities for most crops grown in the western states. Consumptive-use values (U) were measured, and these data were correlated with temperature and growing season. Crop consumptive-use coefficients were then computed by the formula:

$$K = \frac{U}{F}$$

The computed coefficients varied somewhat because of the diverse conditions, such as soils, water supply, and methods, under which the studies were conducted. These coefficients were adjusted where necessary after the data were analyzed. The resulting coefficients are believed to be suitable for use under normal conditions.

While only very limited investigations of consumptive use have been made in the Eastern or humid-area States, studies made thus far fail to indicate that there should be any great difference between the seasonal consumptive-use coefficients used there and those used in the Western States.

Table 2A–2 shows the values of seasonal consumptive-use crop coefficients currently proposed by Blaney-Criddle for most irrigated crops. Ranges in the values of these coefficients are shown. The values, however, are not all inclusive limits. In some circumstances, K values may be either higher or lower than shown.

Monthly or short-time consumptive-use coefficients

Although seasonal coefficients (K) as reported by various investigators show some variation for the same crops, monthly or short-time coefficients (k) show even greater variation. These great variations are influenced by a number of factors that must be considered when computing or estimating short-time coefficients. Although these factors are numerous, the most important are temperature and the growth stage of the crop.

Table 2A–2 Seasonal consumptive-use crop coefficients (K) for irrigated crops

Crop	Length of normal growing season or period 1/	Consumptive-use coefficient (K) 2/
Alfalfa	Between frosts	0.80 to 0.90
Bananas	Full year	.80 to 1.00
Beans	3 months	.60 to .70
Cocoa	Full year	.70 to .80
Coffee	Full year	.70 to .80
Corn (maize)	4 months	.75 to .85
Cotton	7 months	.60 to .70
Dates	Full year	.65 to .80
Flax	7 to 8 months	.70 to .80
Grains, small	3 months	.75 to .85
Grain, sorghum	4 to 5 months	.70 to .80
Oilseeds	3 to 5 months	.65 to .75
Orchard crops:		
Avocado	Full year	.50 to .55
Grapefruit	Full year	.55 to .65
Orange and lemon	Full year	.45 to .55
Walnuts	Between frosts	.60 to .70
Deciduous	Between frosts	.60 to .70
Pasture crops:		
Grass	Between frosts	.75 to .85
Ladino whiteclover	Between frosts	.80 to .85
Potatoes	3 to 5 months	.65 to .75
Rice	3 to 5 months	1.00 to 1.10
Soybeans	140 days	.65 to .70
Sugar beet	6 months	.65 to .75
Sugarcane	Full year	.80 to .90
Tobacco	4 months	.70 to .80
Tomatoes	4 months	.65 to .70
Truck crops, small	2 to 4 months	.60 to .70
Vineyard	5 to 7 months	.50 to .60

1/ Length of season depends largely on variety and time of year when the crop is grown. Annual crops grown during the winter period may take much longer than if grown in the summertime.

2/ The lower values of K for use in the Blaney-Criddle formula, U=KF, are for the more humid areas, and the higher values are for the more arid climates.

Growing season

In using the Blaney-Criddle formula for computing seasonal requirements, the potential growing season for the various crops is normally considered to extend from frost to frost or from the last killing frost in the spring to the end of a definite period thereafter. For most crops, this is adequate for seasonal use estimates, but a refinement is necessary to more precisely define the growing season when monthly or short-time use estimates are required. In many areas records are available from which planting, harvesting, and growth dates can be determined. These records should be used where possible. In other areas temperature data may be helpful for estimating these dates. Table 2A–3 gives some guides that can help determine these dates.

The spring frost date corresponds very nearly with a mean temperature of 55 degrees, so it is obvious that many of the common crops use appreciable amounts of water before the last frost in the spring and may continue to use water after the first front in the fall.

Climate coefficient (k_t)

While it is recognized that a number of climatological factors affect consumptive use by crops, seldom is complete climatological data on relative humidity, wind movement, sunshine hours, or pan evapotranspiration available for a specific site. Thus, it is necessary to rely on records of temperature that are widely available.

In 1954, J.T. Phelan attempted to correlate the monthly consumptive-use coefficient (k) with the mean monthly temperature (t). It was noted that a loop effect occurred in the plotted points—the computed values of (k) were higher in the spring than in the fall for the same temperature. The effects of this loop were later corrected by the development of a crop growth stage coefficient (k_c). The relationship between (k) and (t) was adopted for computing values of (k_t), the temperature coefficient. This relationship is expressed as $k_t = .0173t - .314$. Table 2A–4 gives values of k_t for temperatures ranging from 36 to 100 degrees Fahrenheit.

Table 2A–3 A guide for determining planting dates, maturity dates, and lengths of growing seasons as related to mean air temperature

Crops	Earliest moisture—Use or planting date as related to mean air temperature	Latest moisture—Use or maturing date as related to mean air temperature	Growing season days
Perennial crops			
Alfalfa	50° mean temp.	28° frost	Variable
Grasses, cool	45° mean temp.	45° mean temp.	Variable
Orchards, deciduous	50° mean temp.	45° mean temp.	Variable
Grapes	55° mean temp.	50° mean temp.	Variable
Annual crops			
Beans	60° mean temp.	32° frost	90 — 100
Corn	55° mean temp.	32° frost	140 — Max.
Cotton	62° mean temp.	32° frost	240 — Max.
Grain, spring	45° mean temp.	32° frost	130 — Max.
Potatoes, late	60° mean temp.	32° frost	130 — Max.
Sorghum, grain	60° mean temp.	32° frost	130 — Max.
Sugar beets	28° frost	28° frost	180 — Max.
Wheat, winter			
(fall season)		45° mean temp.	
(spring season)	45° mean temp.		

Crop growth stage coefficients (k_c)

As previously stated, another factor that causes consumptive use to vary widely throughout the growing season is the plant itself. Stage of growth is a primary variable that must be recognized because it is obvious that plants in the rapid growth stage use water at a more rapid rate than will new seedlings. It is also obvious that these variations in consumptive use throughout the growing season will be greater for annual crops than for perennial crops, such as alfalfa, permanent pasture grasses, and orchards.

Table 2A–4 Values of the climate coefficients (k_t) for various mean air temperatures (t)[1]

t (°F)	k_t	t (°F)	k_t	t (°F)	k_t
36	.31	58	.69	80	1.07
37	.33	59	.71	81	1.09
38	.34	60	.72	82	1.11
39	.36	61	.74	83	1.12
40	.38	62	.76	84	1.14
41	.40	63	.78	85	1.16
42	.41	64	.79	86	1.17
43	.43	65	.81	87	1.19
44	.45	66	.83	88	1.21
45	.46	67	.85	89	1.23
46	.48	68	.86	90	1.24
47	.50	69	.88	91	1.26
48	.52	70	.90	92	1.28
49	.53	71	.91	93	1.30
50	.55	72	.93	94	1.31
51	.57	73	.95	95	1.33
52	.59	74	.97	96	1.35
53	.60	75	.98	97	1.36
54	.62	76	1.00	98	1.38
55	.64	77	1.02	99	1.40
56	.66	78	1.04	100	1.42
57	.67	79	1.05		

1 Values of (k_t) are based on the formula, $k_t = .0173\ t - .314$ for mean temperatures less than 36°, use $k_t = .300$.

To recognize these variations in consumptive use, crop growth stage coefficients (k_c) have been introduced into the formula. Values of these coefficients are calculated from research data. Where values of k_c are plotted against time or stage of growth, curves similar to those shown in figures 2A–1 through 2A–25 result. Such curves are used to obtain values of k_c that, when used with appropriate values of k_t will permit a determination of values of monthly or short-time consumptive-use coefficients (k).

Also, the value of k_c might to some extent be influenced by factors other than the characteristics of the plant itself. For this reason, it is not expected that these curves can be used universally. They should, however, be valid over a considerable area and certainly should be of value in areas where no measured consumptive-use data are available.

For annual crops, such as corn, values of k_c are best plotted as a function of a percentage of the growing season. Figure 2A–7 shows the suggested values of k_c for corn.

For perennial crops, values of k_c generally are best plotted on a monthly basis. Figure 2A–1 shows the plotting of such values for alfalfa. Crop growth stage coefficient curves for all crops for which data are available are in this appendix.

Assumptions in applying the formula

To apply results of a consumptive-use-of-water study in one area to other areas, certain assumptions must be made. If sufficient basic information is available locally, such actual data should be used; however, sufficient detail of the needed data is rarely available. Where necessary information is unavailable, the following assumptions must be made in applying the consumptive-use formula to transfer data between areas:

- Seasonal consumptive use (U) of water varies directly with the consumptive-use factor (F).
- Crop growth and yields are not limited by inadequate water at any time during the growing season.

- Growing periods for alfalfa, pasture, orchard crops, and natural vegetation, although usually extending beyond the frost-free periods, are usually indicated by such periods. Yields of crops dependent only upon vegetative growth vary with the length of the growing period.

Application to specific areas

The application of the Blaney-Criddle formula to specific areas can best be illustrated by examples. Two have been chosen for this purpose. The first is an annual crop, corn, grown in a humid area, Raleigh, North Carolina. The second is a perennial crop, alfalfa, grown in an arid area, Denver, Colorado.

Corn at Raleigh, North Carolina

The procedure for estimating the average daily, monthly, and seasonal consumptive use by corn at this location is shown in sample calculation 2A–1. The average length of the growing season for corn grown near Raleigh is 120 days beginning about April 20.

The estimate is made on a monthly basis, the months and fractions thereof being shown in column 1. The midpoint date for each month or fraction is shown in column 2. The accumulated number of days from the planting date, April 20, to the midpoint of each month or period is shown in column 3. The percentage of the 120-day growing season represented by these midpoint dates is shown in column 4. Thus:

$$\text{column 4} = \frac{\text{column 3}}{120}$$

Mean monthly air temperature values, shown in column 5, are taken from Weather Bureau records. The mean temperature is assumed to occur on the 15th day of each month. The mean air temperature for a part of a month can be obtained mathematically or graphically by assuming that the increase or decrease in temperature between the 15th day of any consecutive month is a straight-line relationship. For example, at Raleigh, the mean monthly air temperature for April is 60.6 degrees and that for May is 69.2 degrees. The mean air temperature for the midpoint date is calculated as follows:

$$60.6° + \frac{10 \text{ days } \left(69.2° - 60.6°\right)}{30 \text{ days}} = 63.5°$$

Sample calculation 2A–1 Estimate of average daily, monthly, and seasonal consumptive-use by corn (harvested for grain) at Raleigh, North Carolina, latitude 35°47' N

(1) Month or period	(2) Midpoint of period	(3) Accum. days to midpoint	(4) Percent of growing season	(5) Mean air temp., t (°F)	(6) Daylight hours, p (%)	(7) Cons. use factor, f	(8) Climatic coeff., k_t	(9) Growth stage coeff., k_c	(10) Cons. use coeff., k	(11) Monthly cons. use, u (in)	(12) Daily cons. use, u (in/d)
April 20											
	April 25	5	4.2	63.5	3.05	1.94	.79	.46	.36	.70	.070
May											
	May 15	25	20.8	69.2	9.79	6.77	.88	.59	.52	3.52	.114
June											
	June 15	56	46.7	76.9	9.81	7.54	1.02	1.02	1.04	7.84	.261
July											
	July 15	86	71.7	79.4	9.98	7.92	1.06	1.05	1.11	8.79	.284
August											
	Aug. 9	111	92.5	78.3	5.52	4.32	1.04	.91	.95	4.10	.228
Aug. 18											
Season total										24.95 inches	

Raleigh is located at latitude 35°47' N. The monthly percentages of daylight hours, shown in column 6, are taken from table 2A–1. For parts of a month, the values of these percentages can be obtained in a similar manner as that described for mean air temperature. For example, at Raleigh, the monthly percentage of daylight hours for April is 8.84 and that for May is 9.79. For the period April 20 through April 30, the monthly percentage of daylight hours is calculated as:

$$\left(8.84\% + \frac{10\text{ days}\left(9.79\% - 8.84\%\right)}{30\text{ days}}\right)\frac{10\text{ days}}{30\text{ days}} = 3.05\%$$

The values of consumptive use factors (f) shown in column 7 are the product of t and p divided by 100. Values of the climatic coefficient (k_t) shown in column 8 are taken from table 2A–4. Values of the crop growth stage coefficient (k_c) shown in column 9 are taken from the curve shown in figure 2A–7. The values of the monthly consumptive-use coefficient (k) shown in column 10 are the product of k_t and k_c. Values of monthly consumptive use (u) shown in column 11 are the product of values of k and f. The average daily rates of consumptive use shown in column 12 are the monthly values of u (column 11) divided by the number of days in the month.

Alfalfa in Denver, Colorado

The procedure for estimating the average daily, monthly, and seasonal consumptive use by alfalfa in this location is shown in sample calculation 2A–2. The growing season for alfalfa grown near Denver is considered to be that period from the date corresponding to 50° mean temperature in the spring to the date corresponding to 28° frost in the fall. This period is from April 24 to October 25.

The procedure illustrated by sample calculation 2A–2 is the same as that described for corn in sample calculation 2A–1. The values of the crop growth stage coefficient (k_c) shown in column 8 are taken from the curve for alfalfa shown in figure 2A–1.

Sample calculation 2A–2 Estimate of average daily, monthly, and seasonal consumptive use by alfalfa at Denver, Colorado

(1) Month or period	(2) Midpoint of period	(3) Days in period	(4) Mean air temp, t (°F)	(5) Daylight hours, p (%)	(6) Cons. use factor, f	(7) Climatic coeff., k_t	(8) Growth stage coeff., k_c	(9) Cons. use coeff., k	(10) Monthly cons. use, u (in/mo)	(11) Daily cons. use, u (in/d)
April 24										
	April 27	6	51.1	1.87	0.96	0.57	1.03	0.59	0.57	0.095
May										
	May 15	31	56.3	9.99	5.62	0.66	1.08	0.71	3.99	0.129
June										
	June 15	30	66.4	10.07	6.69	0.84	1.13	0.95	6.36	0.212
July										
	July 15	31	72.8	10.20	7.43	0.95	1.11	1.05	7.80	0.252
August										
	August 15	31	71.3	9.54	6.80	0.92	1.06	0.98	6.66	0.215
September										
	Sept. 15	30	62.7	8.39	5.26	0.77	0.99	0.76	4.00	0.133
October										
	Oct. 12	25	53.5	6.31	3.38	0.61	0.91	0.56	1.89	0.076
Oct. 25										
Seasonal total									31.27 inches	

Figure 2A–1 Crop growth stage coefficient curve for alfalfa

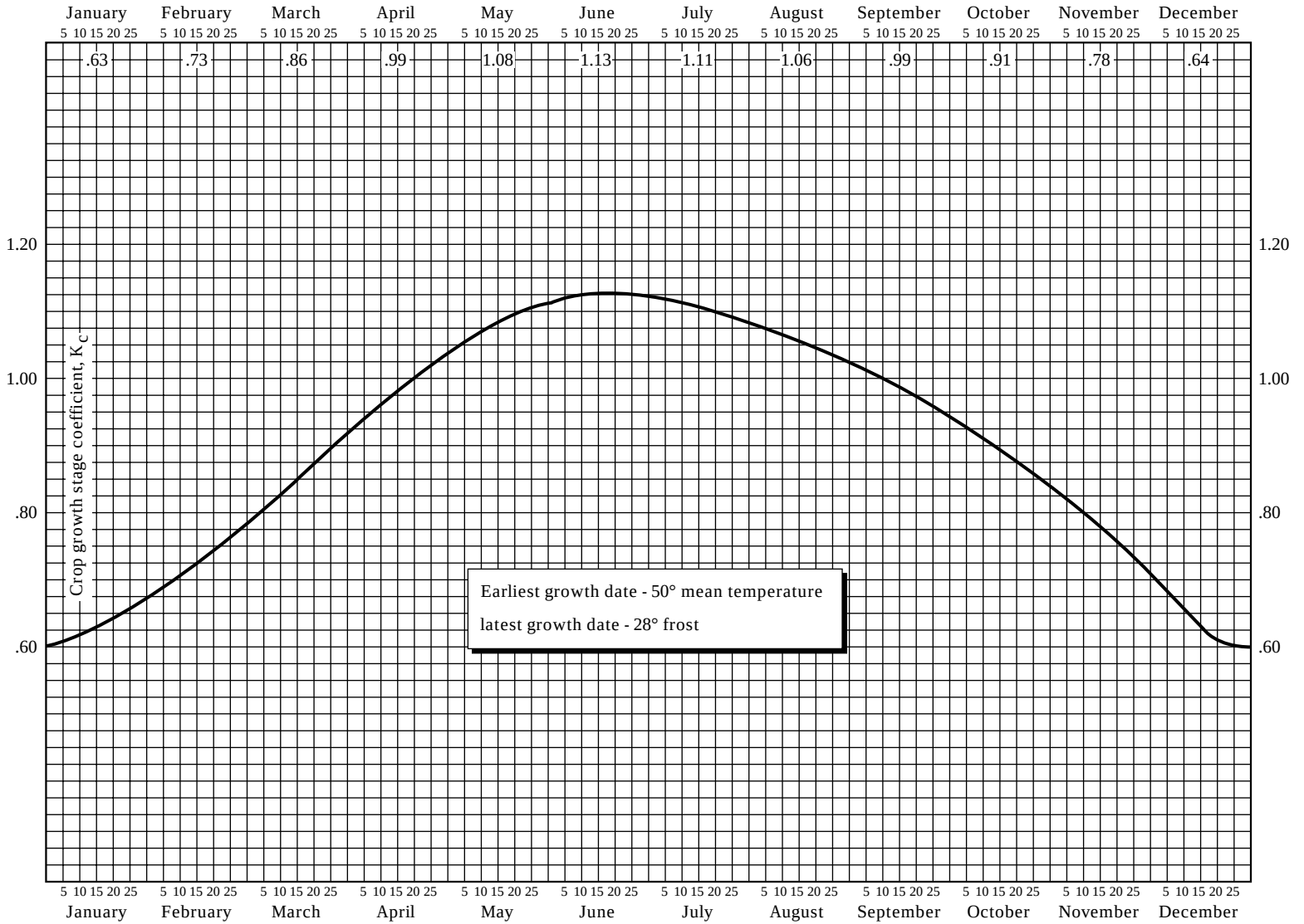


Figure 2A–2 Crop growth stage coefficient curve for avocados

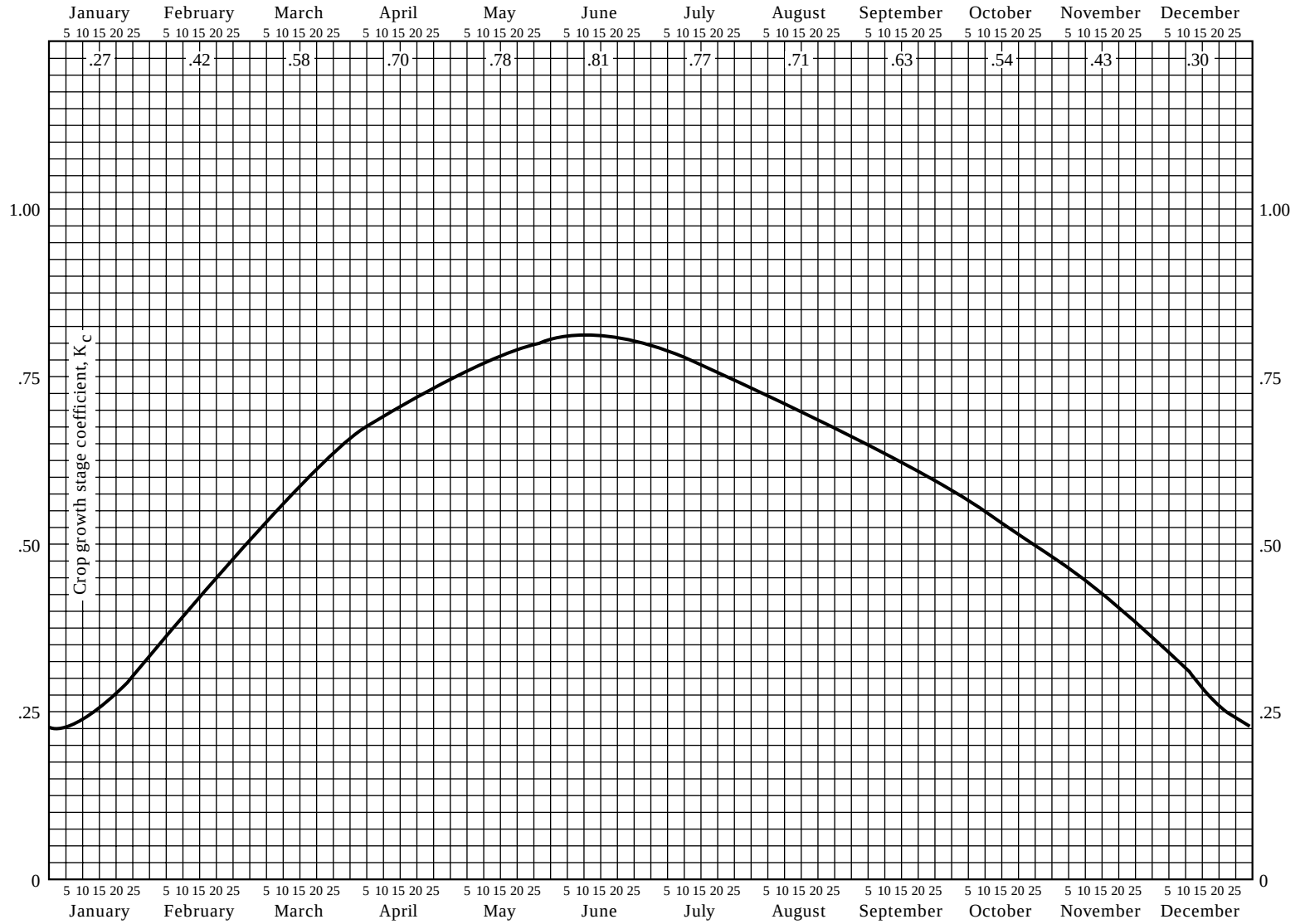


Figure 2A–3 Crop growth stage coefficient curve for dry beans

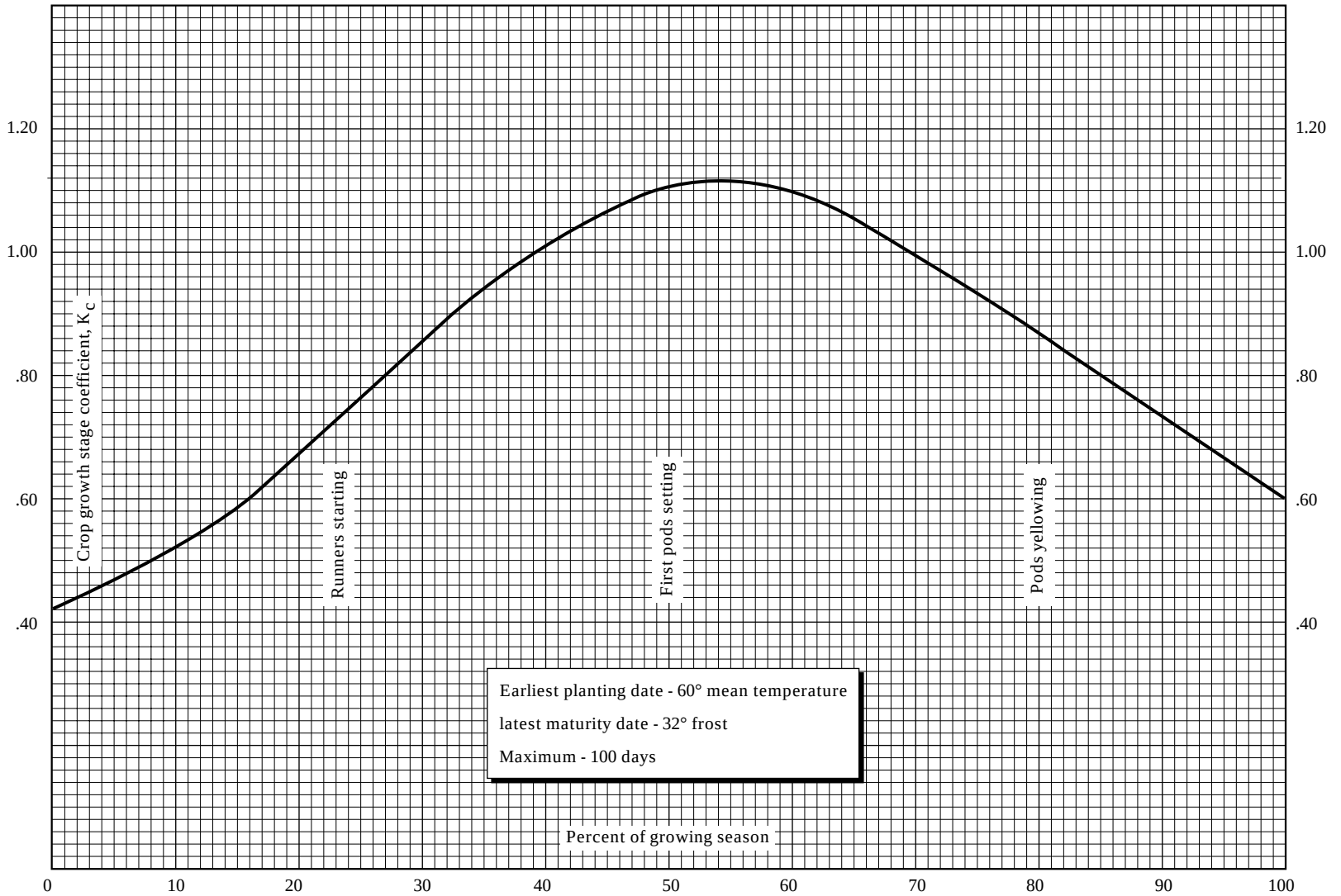


Figure 2A–4 Crop growth stage coefficient curve for snap beans

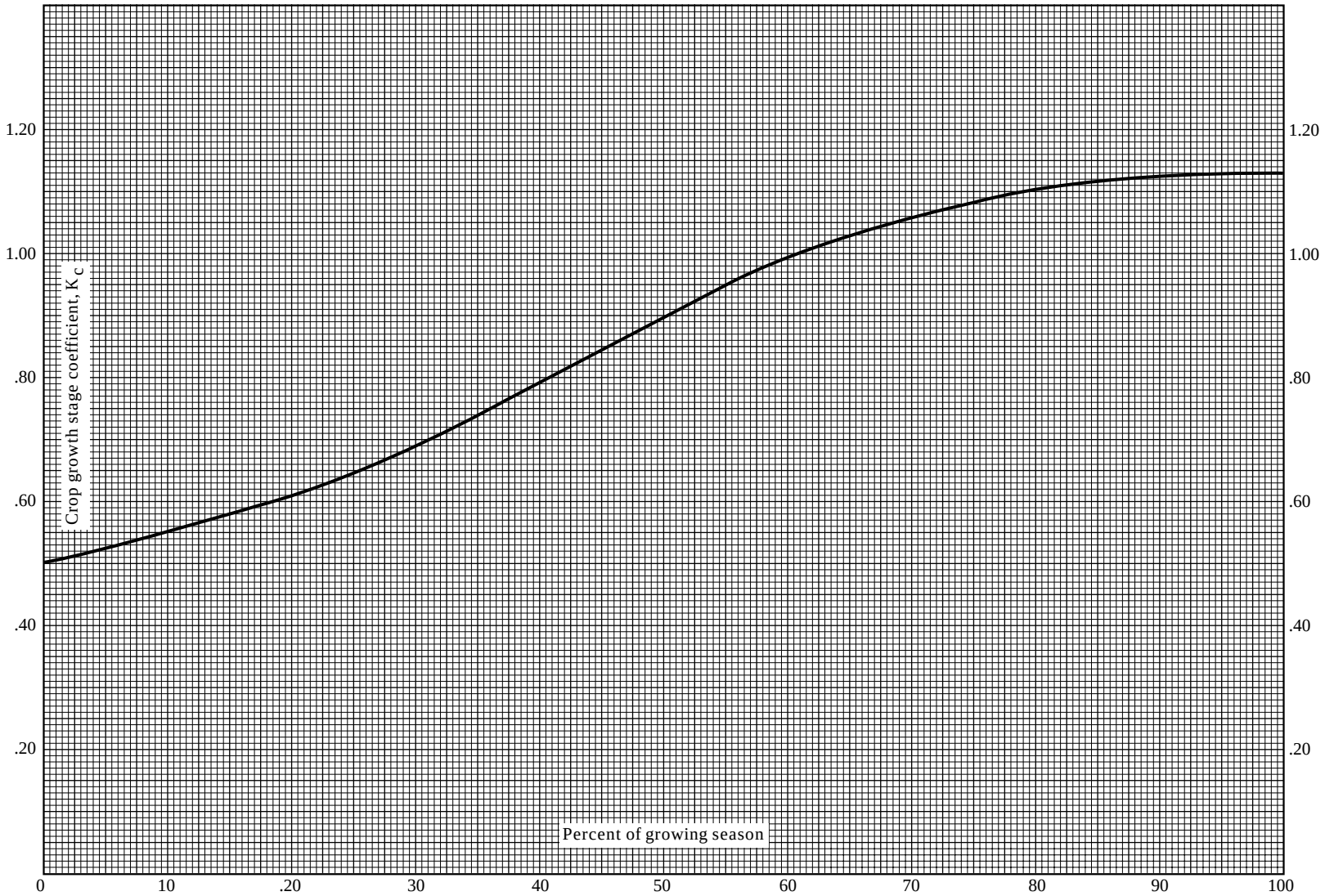


Figure 2A–5 Crop growth stage coefficient curve for sugar beets

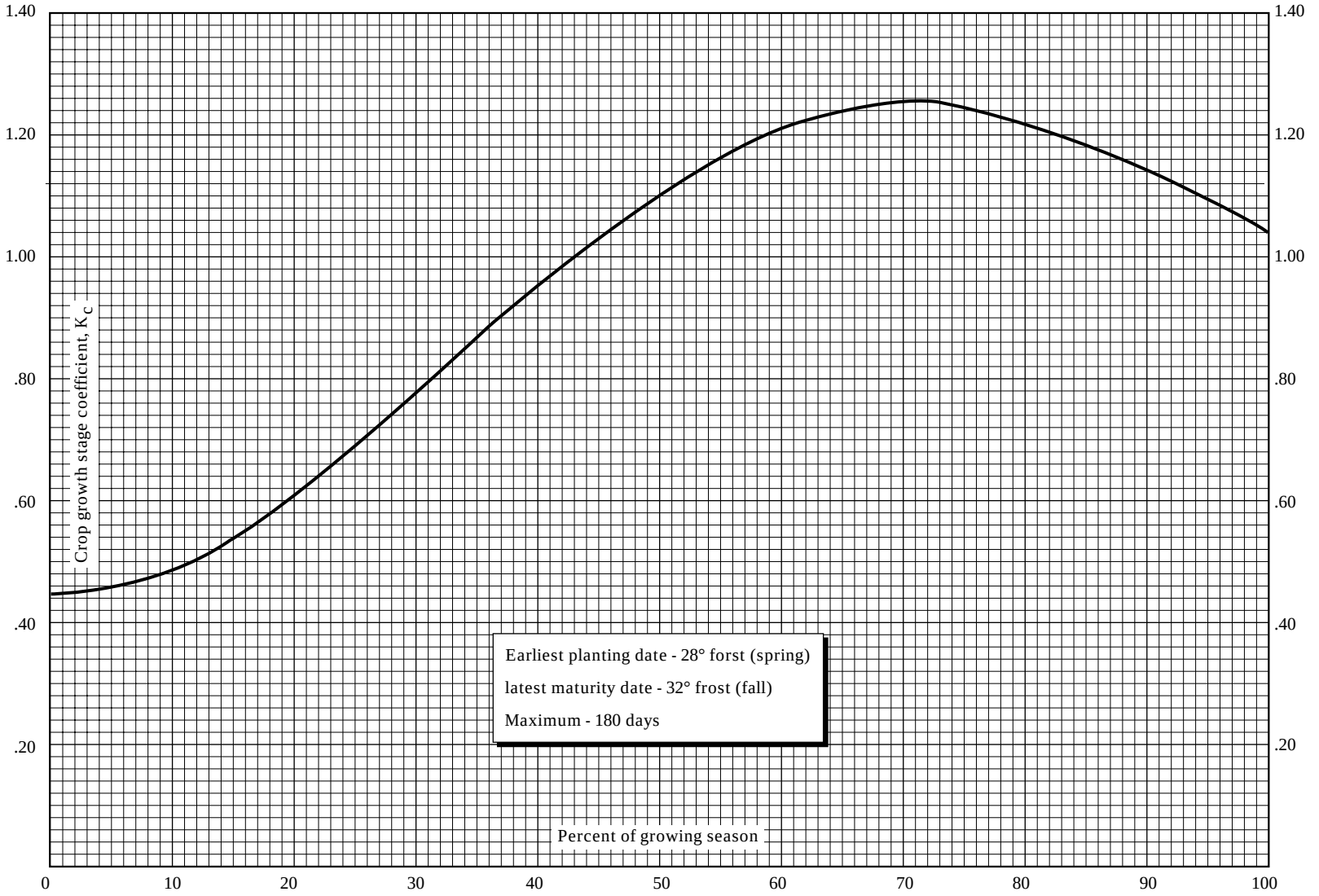


Figure 2A–6 Crop growth stage coefficient curve for citrus

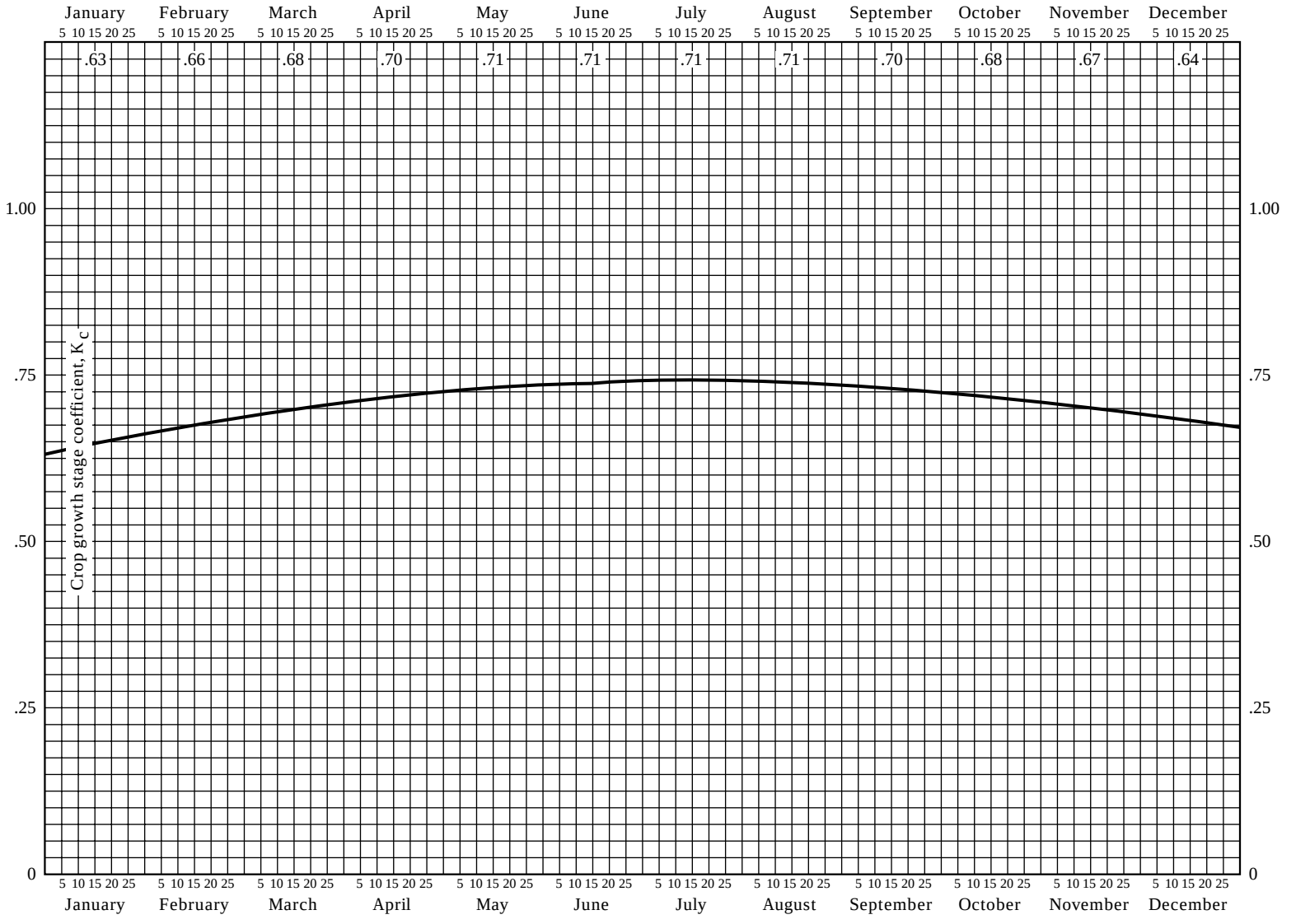


Figure 2A–7 Crop growth stage coefficient curve for corn (grain)

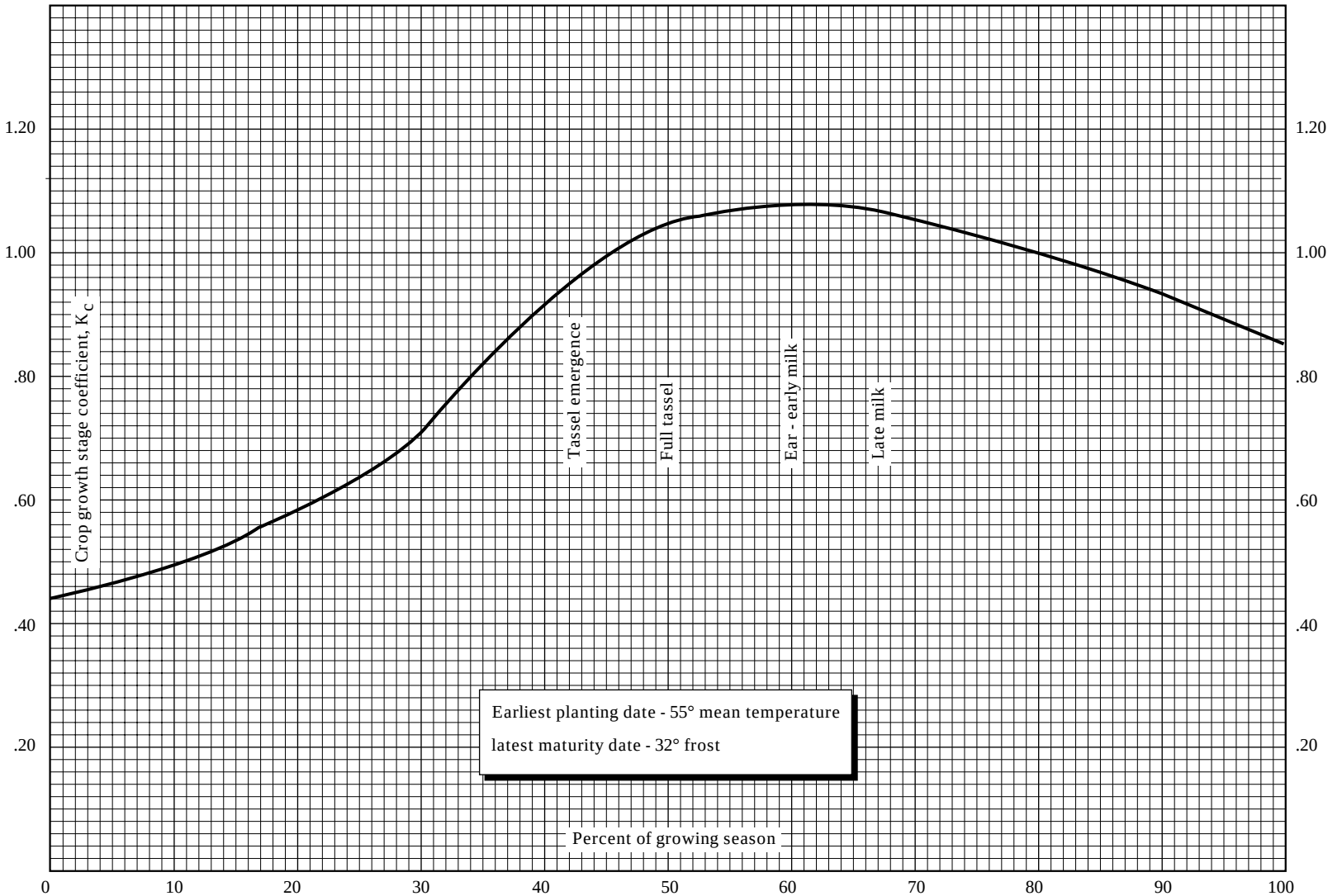


Figure 2A–8 Crop growth stage coefficient curve for corn (silage)

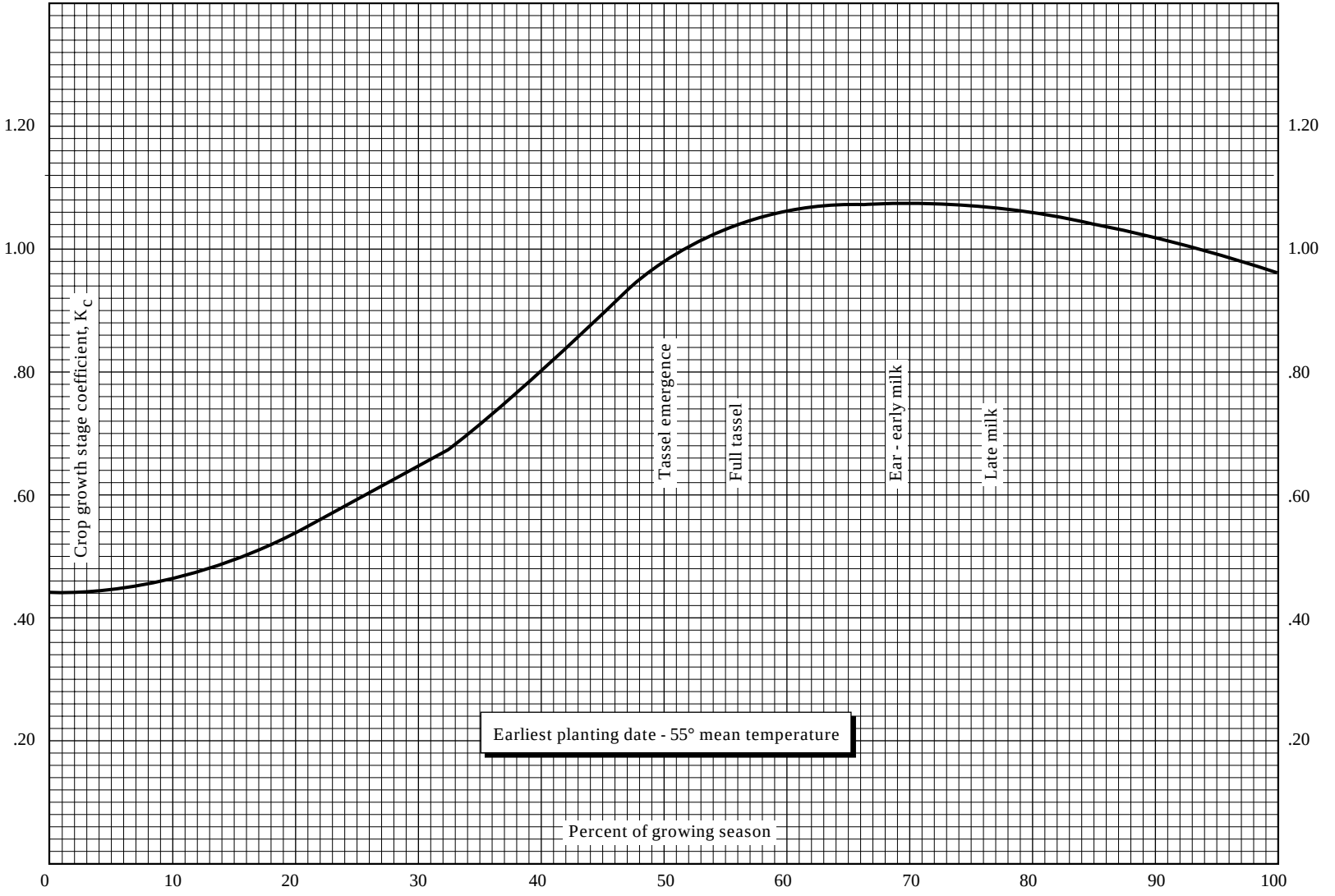


Figure 2A–9 Crop growth stage coefficient curve for sweet corn

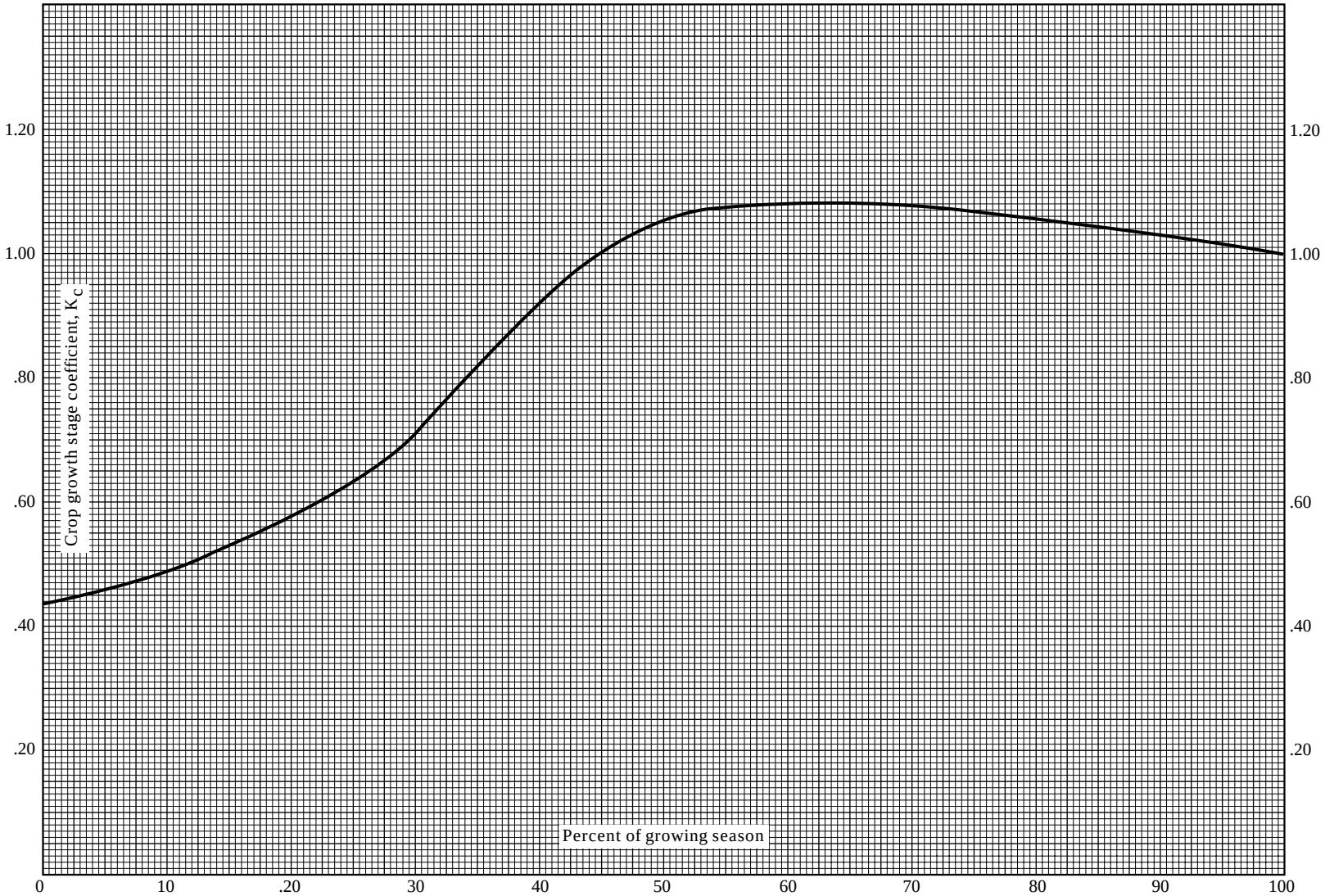


Figure 2A–10 Crop growth stage coefficient curve for cotton

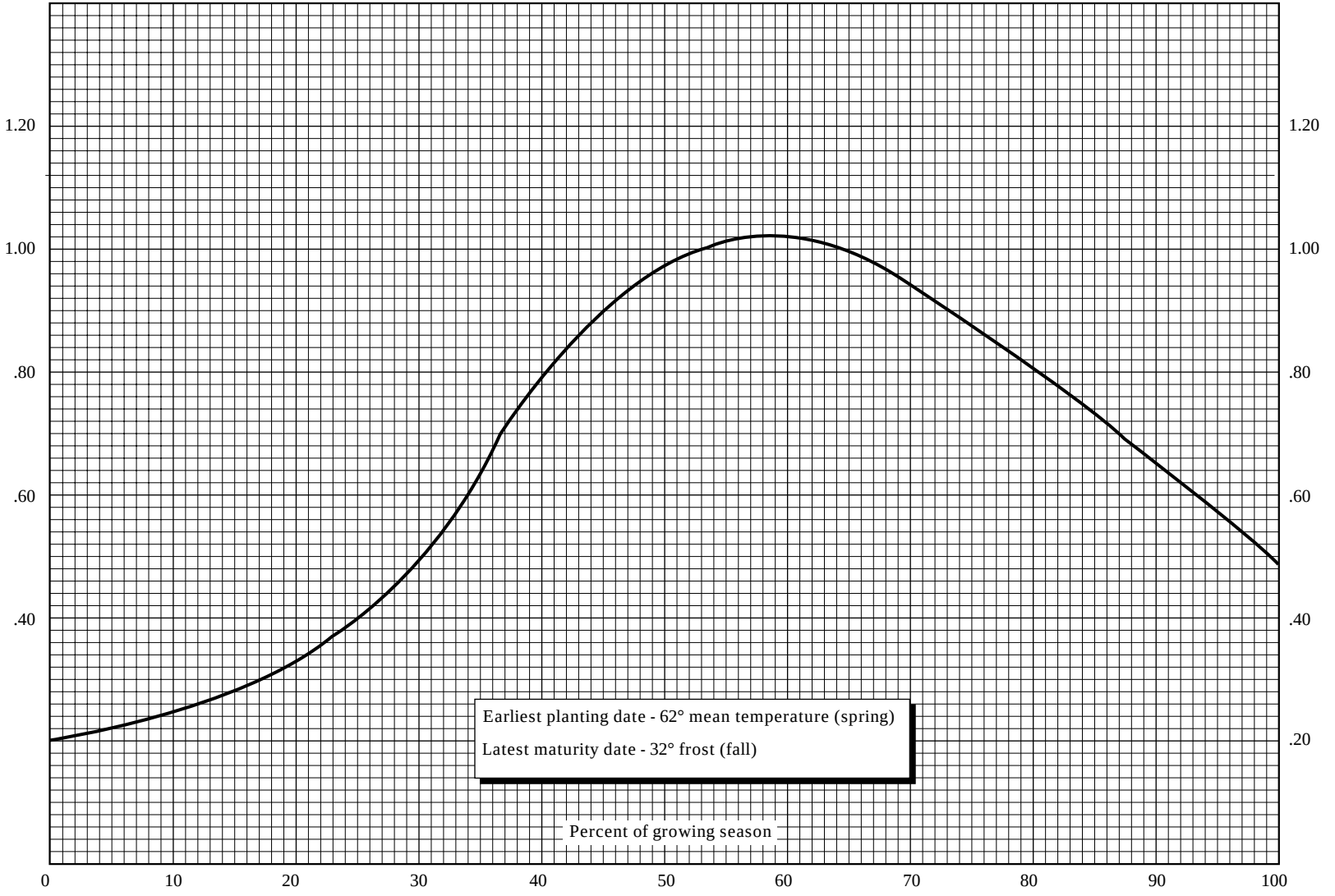


Figure 2A–11 Crop growth stage coefficient curve for spring grain

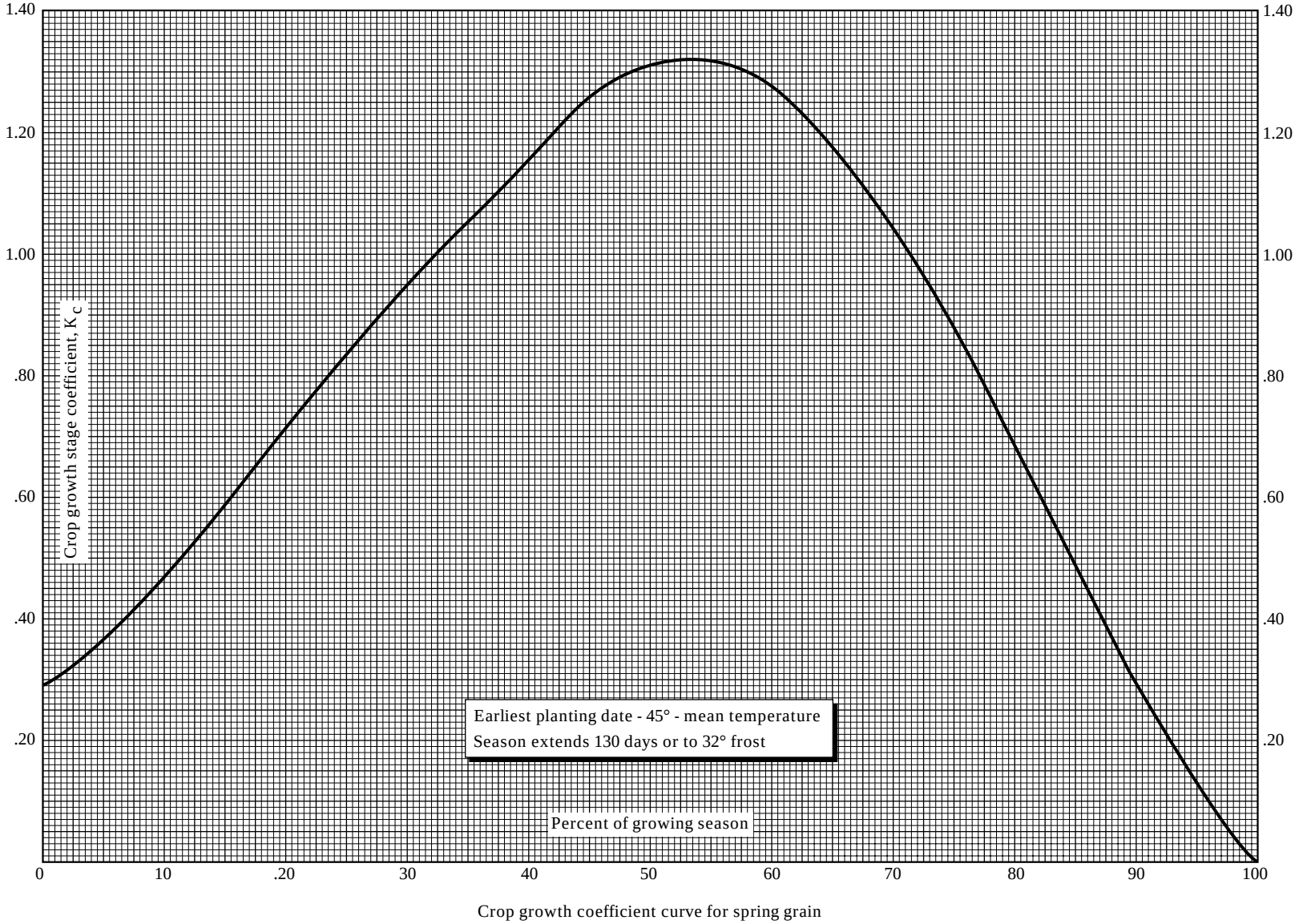


Figure 2A–12 Crop growth stage coefficient curve for grapes

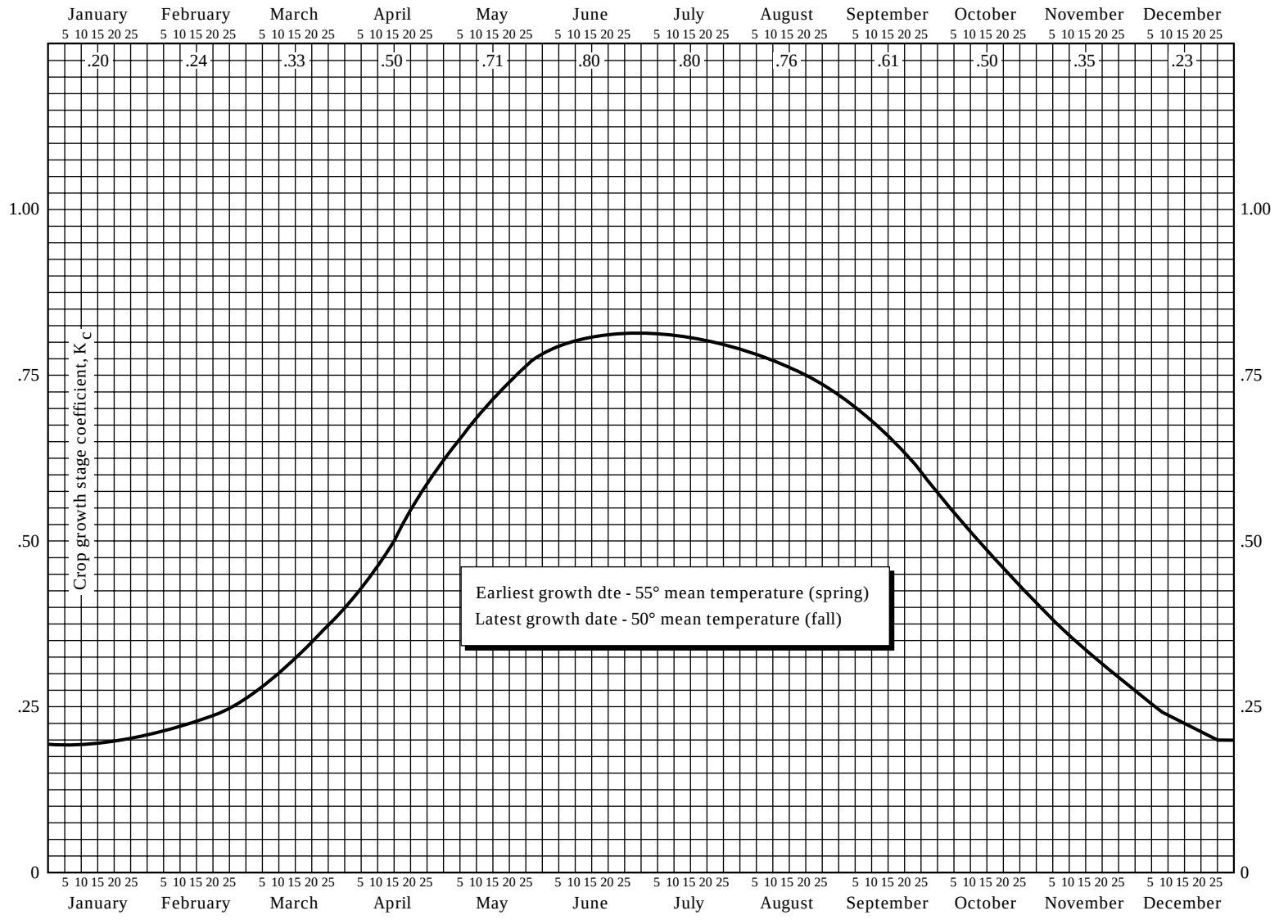


Figure 2A–13 Crop growth stage coefficient curve for melons and cantaloupes

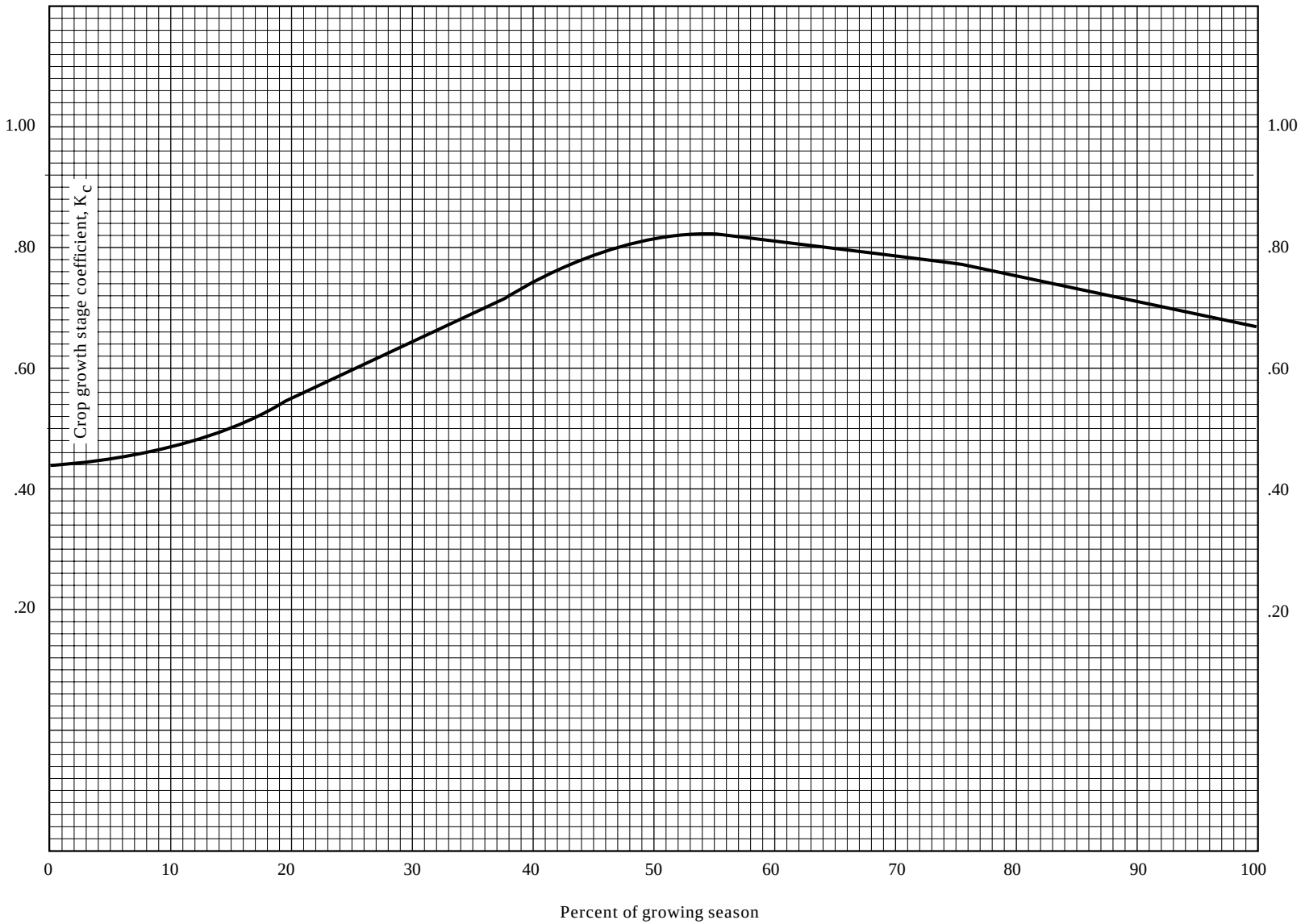


Figure 2A–14 Crop growth stage coefficient curve for deciduous orchards

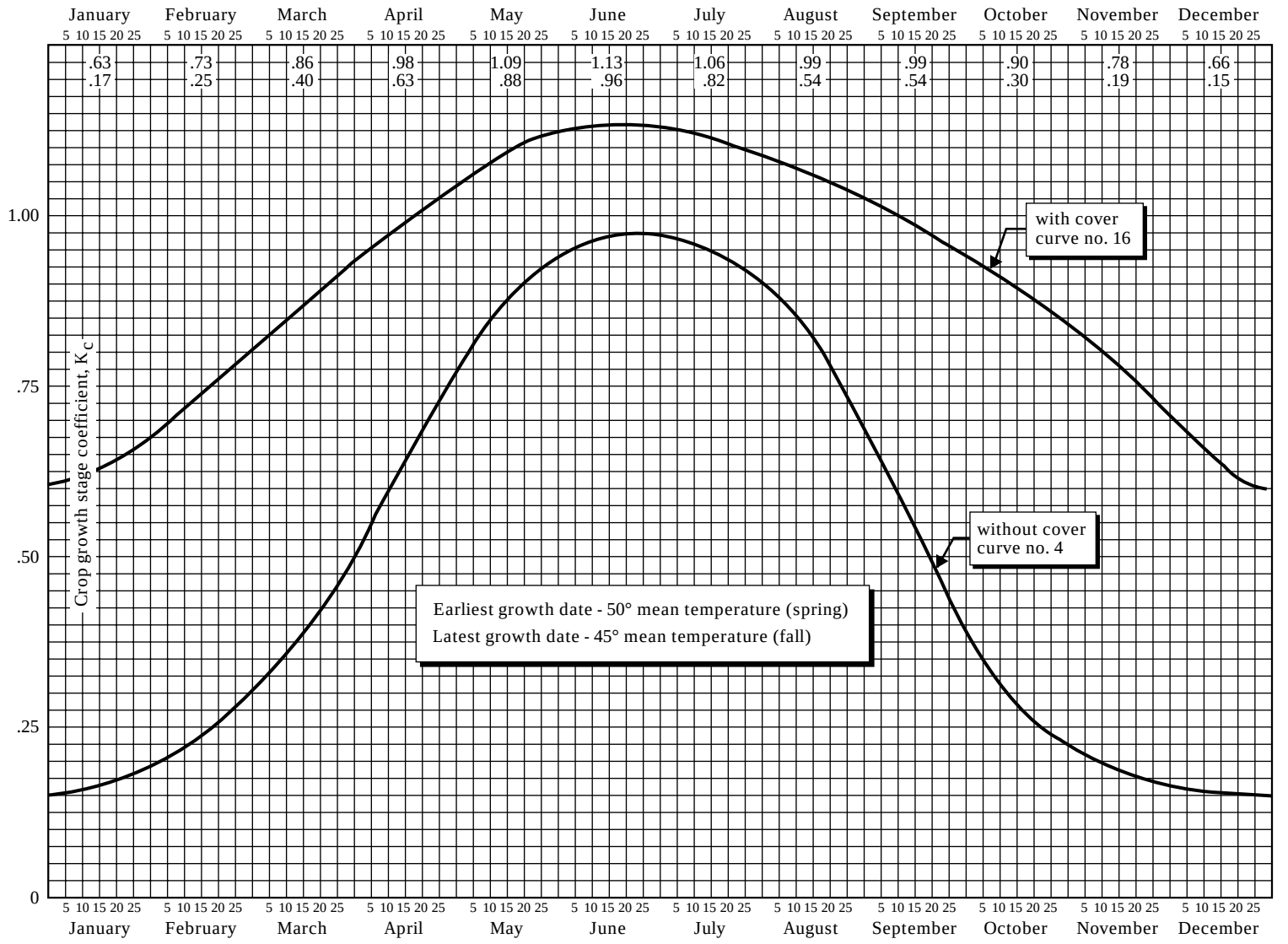


Figure 2A–15 Crop growth stage coefficient curve for pasture grasses

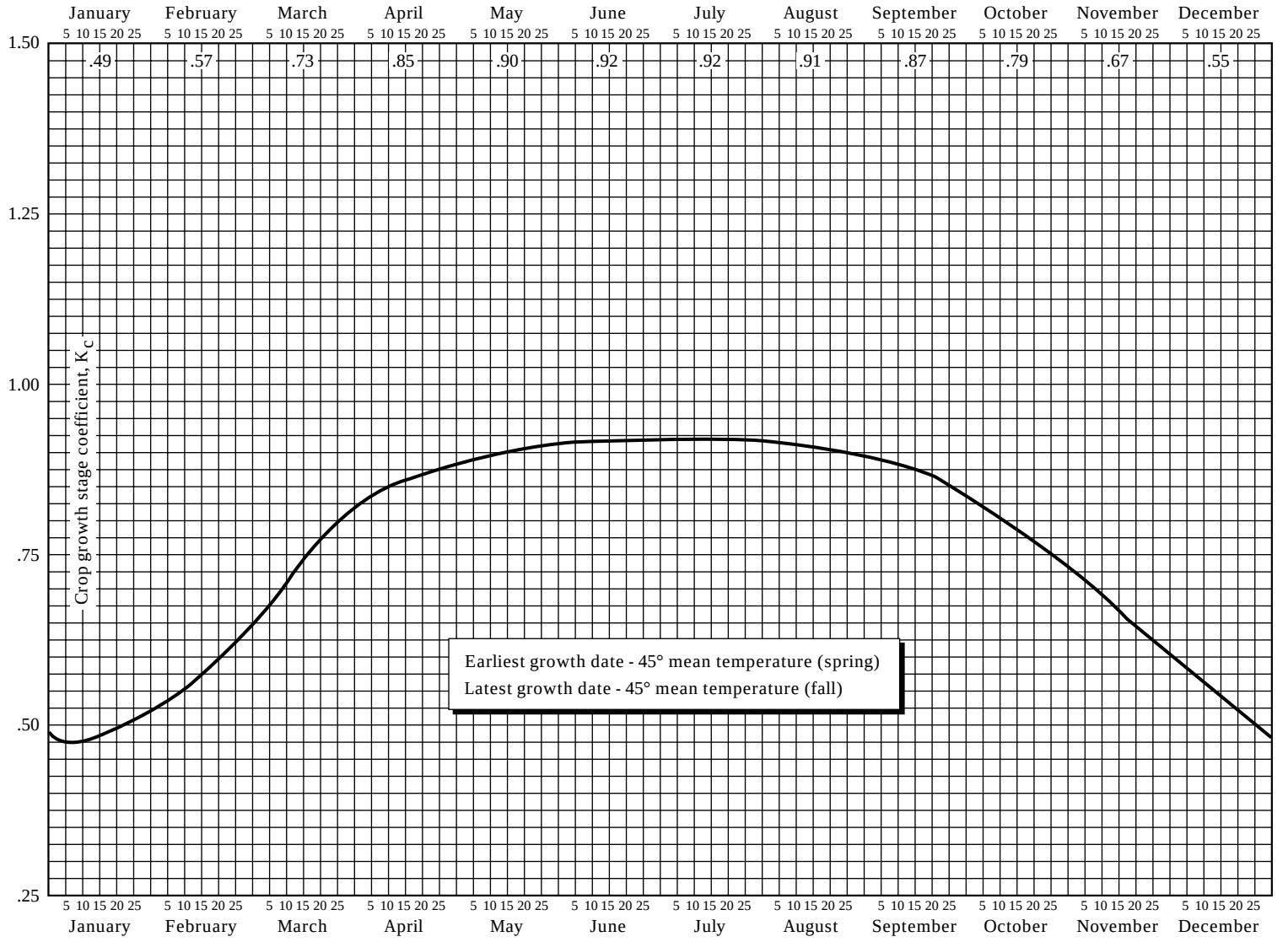


Figure 2A–16 Crop growth stage coefficient curve for peas

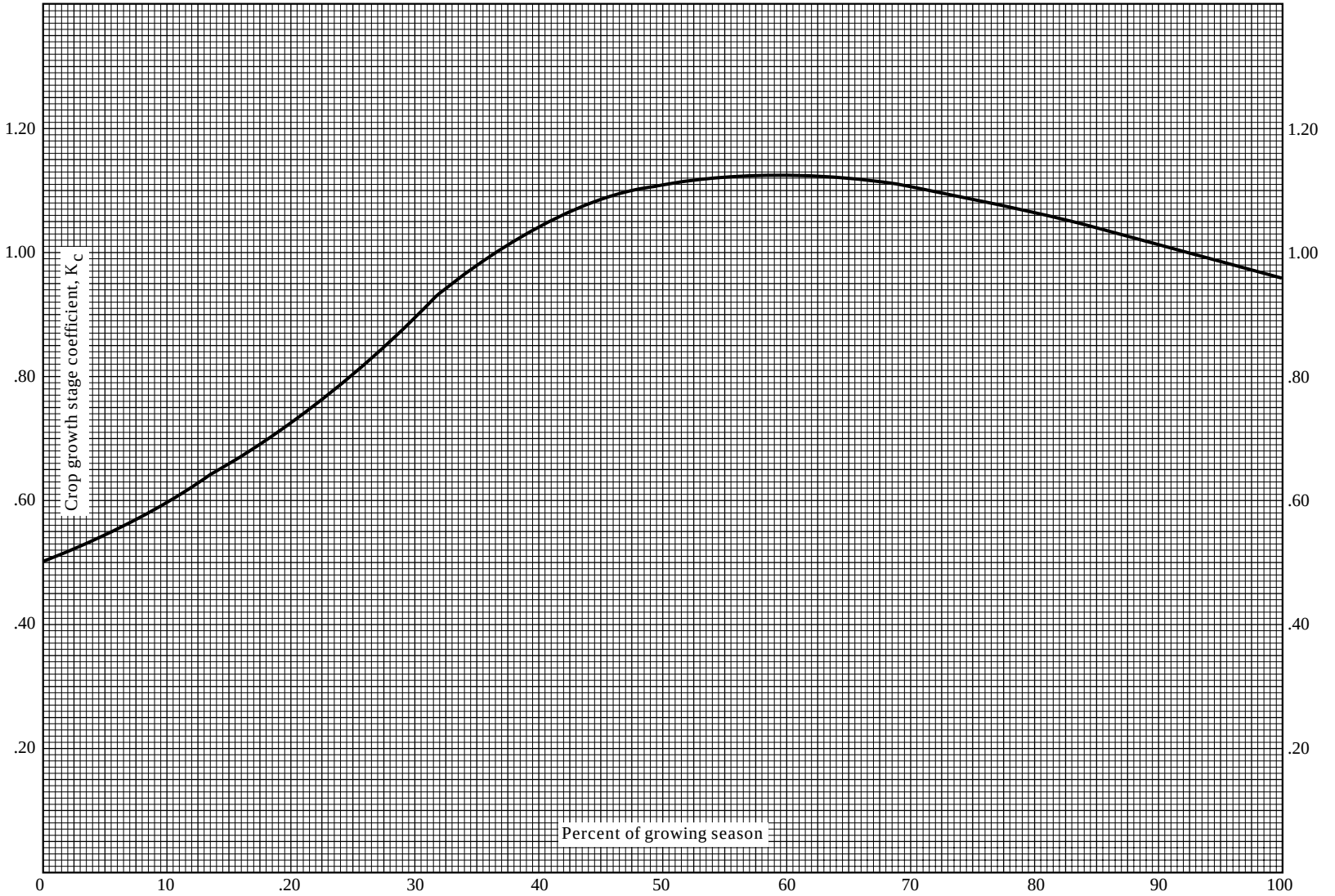
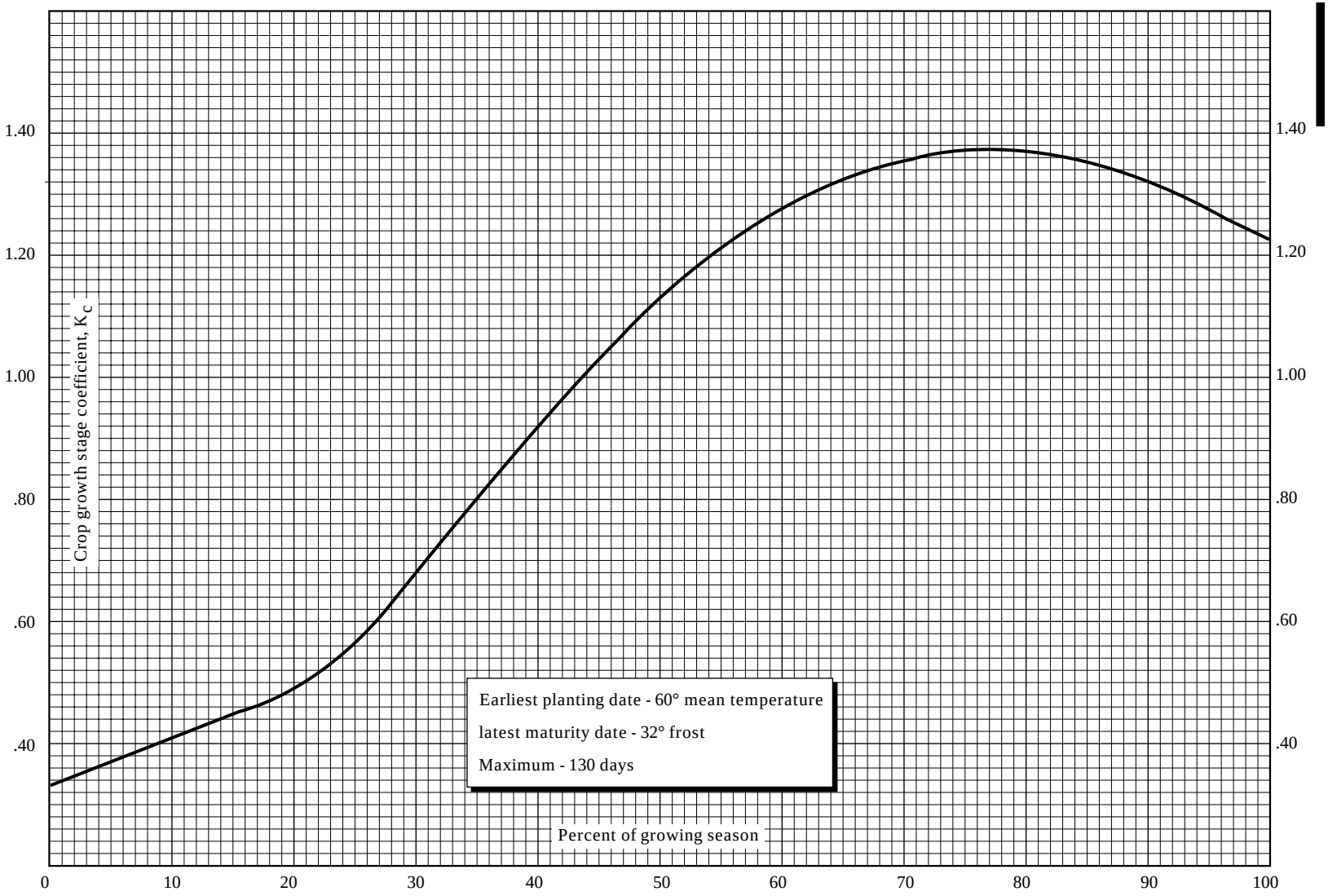


Figure 2A–17 Crop growth stage coefficient curve for Irish potatoes



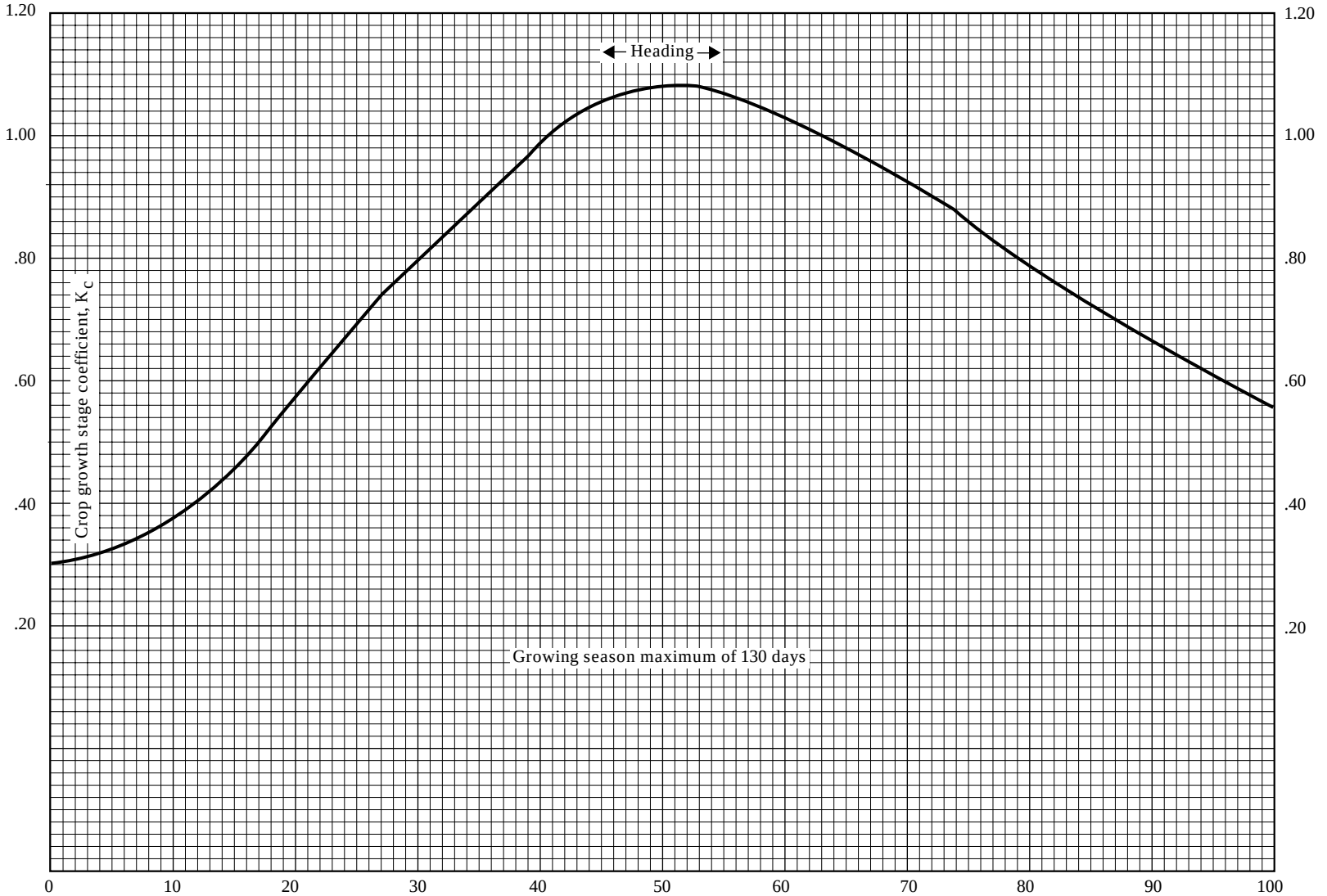


Figure 2A–18 Crop growth stage coefficient curve for grain sorghum

Figure 2A–19 Crop growth stage coefficient curve for soybeans

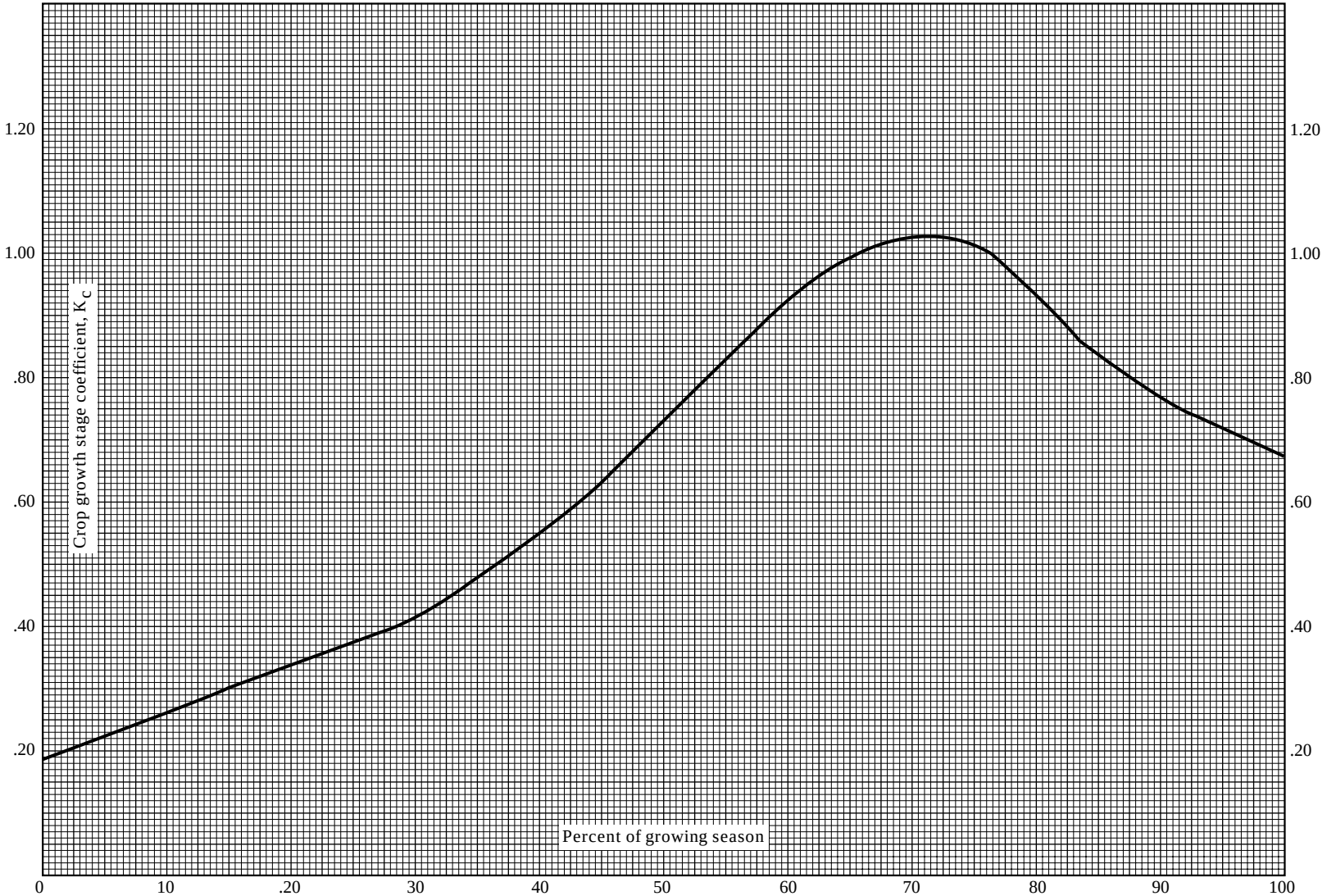


Figure 2A–20 Crop growth stage coefficient curve for tomatoes

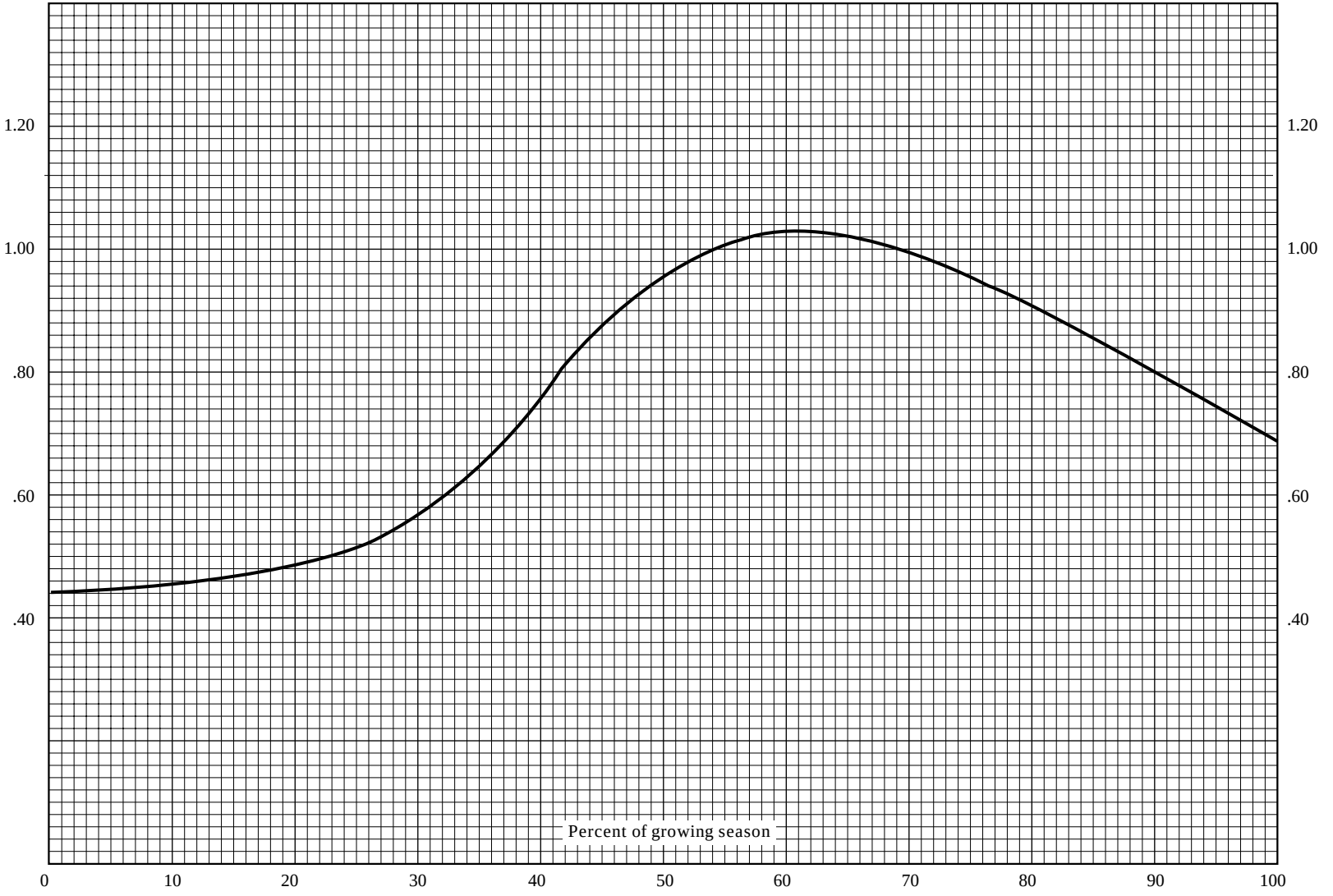
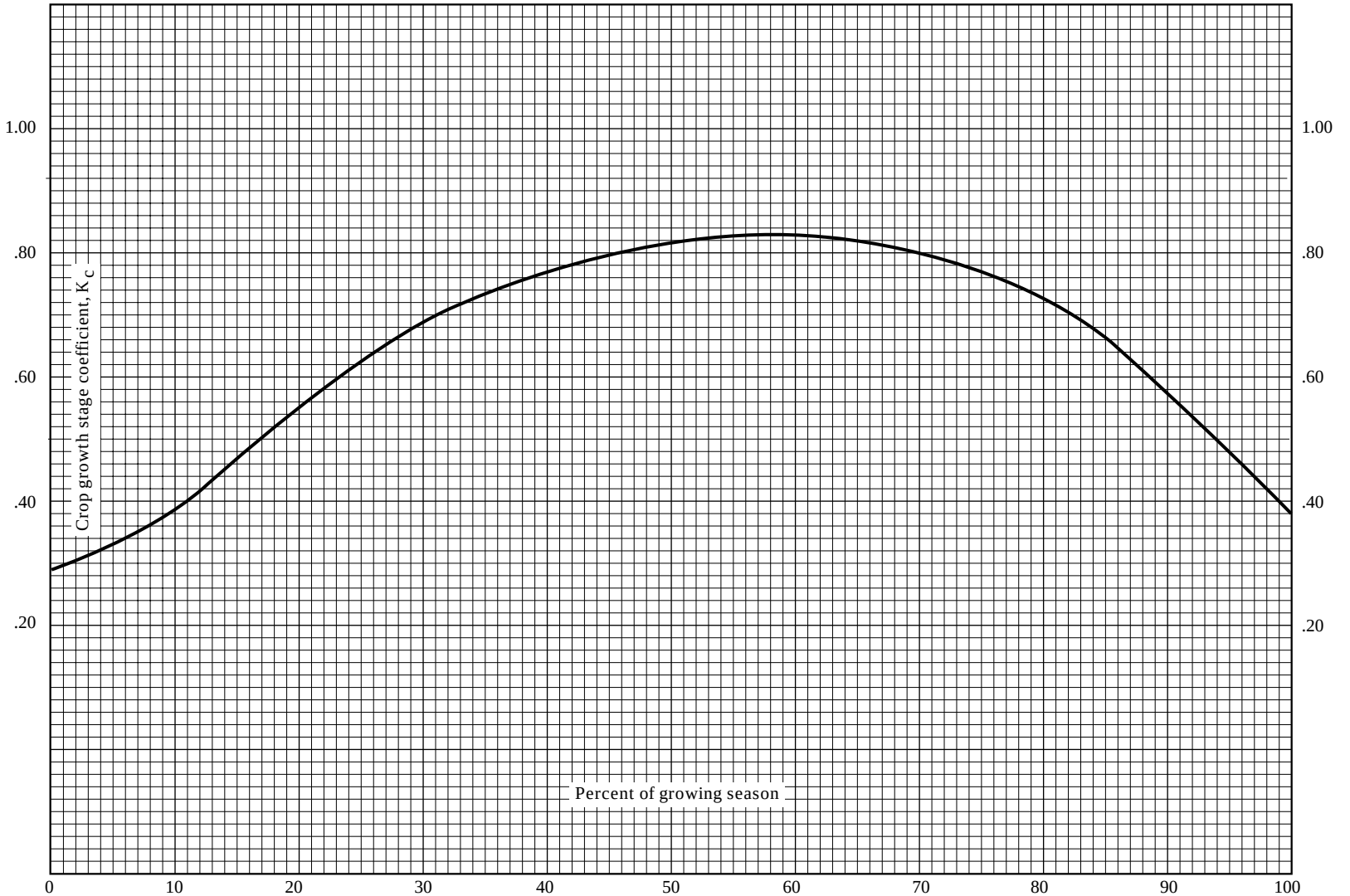


Figure 2A–21 Crop growth stage coefficient curve for small vegetables



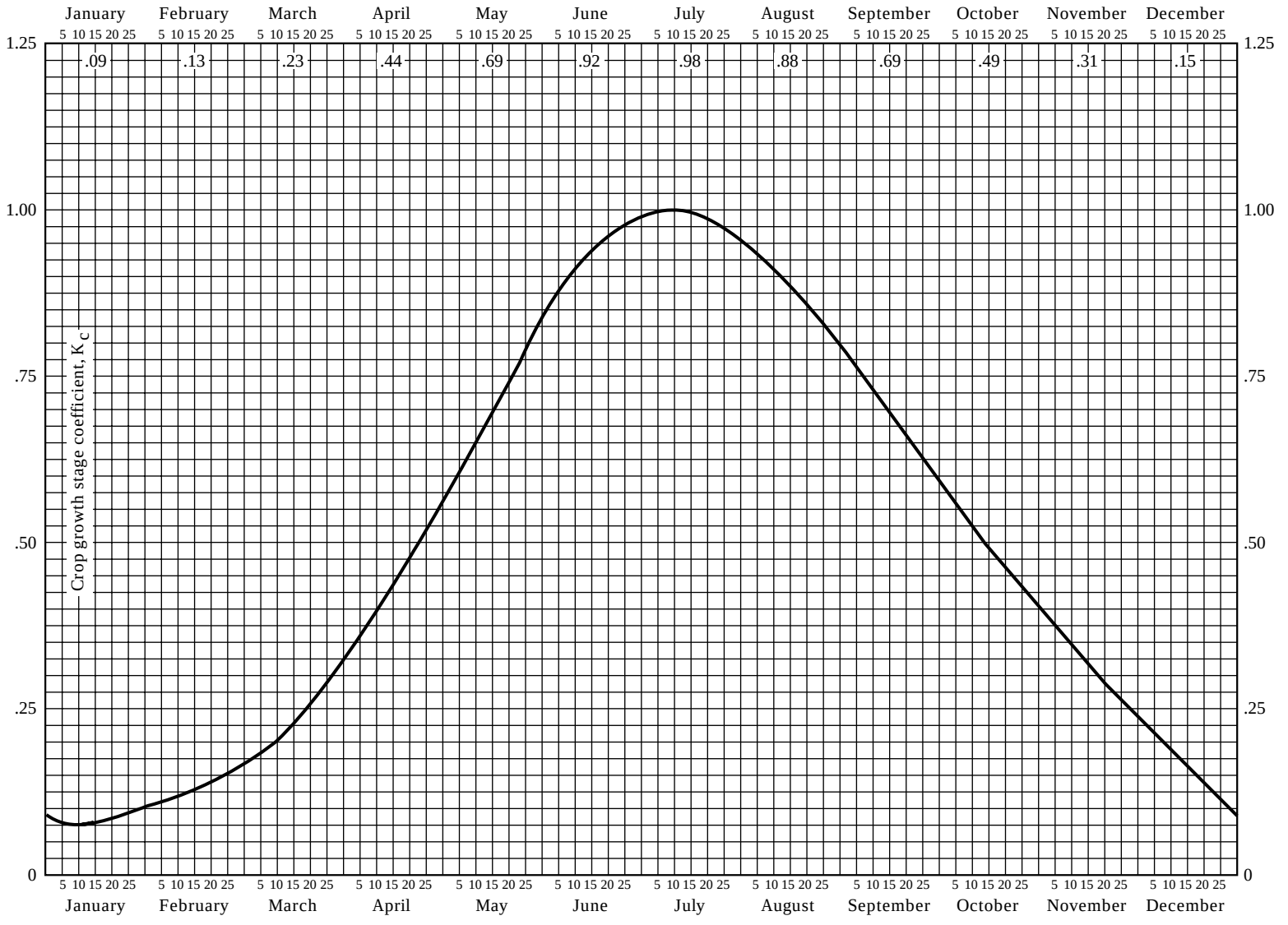
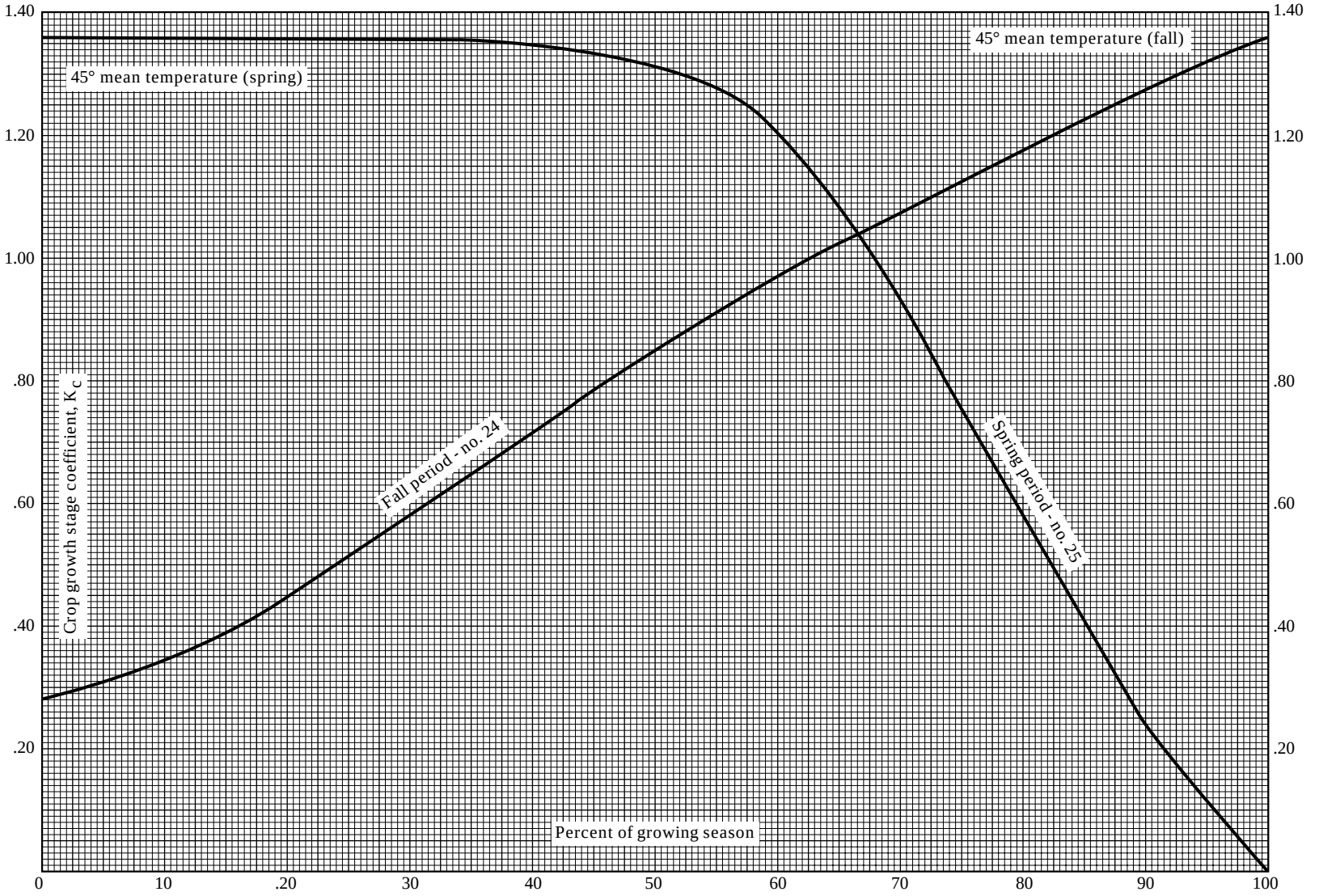


Figure 2A–22 Crop growth stage coefficient curve for walnuts

Figure 2A–23 Crop growth stage coefficient curve for winter wheat



Appendix B Day of Year Calendar

Day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

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Glossary

Advection (A_d) Transfer of heat from hot dry air to crop canopies causing an increase in evapotranspiration. Effects are accelerated under windy conditions.

Albedo (α) The portion of incoming solar radiation that is reflected away from crop and soil surfaces.

Allowable depletion The amount, or percentage, of available soil water that can be used from the crop root zone without causing plant water stresses that reduce yields.

Application efficiency (E_a) The ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation of water applied, expressed as a percentage.

Application Efficiency Low Half (AELH) The ratio of the average of the low one-half of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage.

Application Efficiency Low Quarter (AELQ) The ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage.

Average crop coefficient (K_a) A crop coefficient used to compute evapotranspiration for a period of time where average conditions are used to account for the effect of water stress and evaporation from wet soil surfaces.

Barometric pressure (BP) The air pressure due to the weight of the earths atmosphere.

Basal crop coefficient (K_{cb}) A coefficient used to relate the evapotranspiration from a crop, that is not stressed for water and where the soil surfaces are dry, to that of a grass reference crop.

Bowen ratio (β) The ratio of the amount of energy used to heat air to the amount of energy used to evaporate water.

Carryover soil moisture Moisture stored in soils within crop root zone depths during the non-growing season, at times when the crop is dormant, or before the crop is planted. This moisture is available to help meet the consumptive water needs of the crop.

Chemigation Application of chemicals to crops through an irrigation system by mixing them with the irrigation water.

Chlorosis The yellowing or bleaching of the green portion of the plant, particularly the leaves. May be caused by disease organisms, nutrient deficiencies, excess water, or other factors, such as low temperature.

Clear sky solar radiation (R_{so}) The amount of solar radiation that would be received on a cloud free day.

Coefficient of uniformity (CU) Christiansens Uniformity. A measure of uniformity of water application across a field or irrigation set.

Combination method One of several forms of methods that use air temperature, relative humidity, solar radiation, and wind speed to predict the evapotranspiration from a reference crop. It is called a combination method because it combines the solar energy with that from advection.

Conveyance efficiency (E_c) The ratio of the water delivered to the total water diverted or pumped into an open channel or pipeline at the upstream end, expressed as a percentage.

Crop coefficient (K_c) The coefficient used to relate crop water use to that for a grass reference crop, or the ratio of crop ET to reference crop ET.

Crop growth stages (S_g) Indices used to quantify the phenological development of crops.

Crop water use (ET_c) The rate of evapotranspiration by a disease-free crop growing in a large field under nearly optimal agronomic conditions including adequate fertilizer, optimum water availability, plant density and weed control.

Cycle time The time required to apply an irrigation to the entire field.

Demand delivery system An irrigation water delivery system where the irrigator can order the rate and duration of water supply for the irrigated field.

Density (ρ) The mass of a quantity per unit volume of the quantity.

Dew point temperature (T_d) The air temperature where water vapor condenses from the air and forms dew.

Distribution uniformity The measure of the uniformity of irrigation water distribution over a field.

Distribution Uniformity (DU) of low one-quarter The ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage.

Earliest irrigation date The earliest time that a field can be irrigated without causing deep percolation at either the first or the last part of the field to be irrigated.

Effective cover date The time during the growing season when the crop develops enough canopy to fully shade the ground surface so that the ET rate reaches the maximum rate possible for that crop in the existing environmental conditions.

Effective precipitation (P_e) Precipitation falling during the growing period of the crop that is available to meet the consumptive water requirements of crops. It does not include precipitation that is lost to deep percolation below the root zone, surface runoff, or evaporation from soil surface.

Electrical conductivity (EC) The property of a substance to transfer an electrical charge (reciprocal of resistance). Used for the measurement of the salt content of an extract from a soil when saturated with water, measured in mmho/cm or dS/m. EC_e of the saturation paste at 77 ˚F (25 °C).

Electrical conductivity of irrigation water (EC_i) — The electrical conductivity of the irrigation water.

Electrical conductivity of applied water (EC_{aw}) — The electrical conductivity of the applied water; irrigation water, plus precipitation.

Emittance (ε) — The amount of longwave radiation given off by an objective, compared to the theoretical amount of longwave radiation that a perfect body would emit.

Evaporation pan — A small pan (48 inch diameter x 10 inches deep) used to estimate the reference crop evapotranspiration rate. Water levels are measured daily in the pan to determine the amount of evaporation.

Evapotranspiration (ET) — The volume of water used as evaporation from soil surfaces plus transpiration from plants.

Exchangeable sodium percentage (ESP) — The degree of saturation of the soil exchange complex with sodium; it may be calculated by the formula:

$$ESP = \frac{\text{exchangeable sodium (meq / 100 g soil)}}{\text{cation exchange capacity (meq / 100 g soil)}}$$

FAO Blaney-Criddle Method — A method that uses air temperature data and long-term records for other parameters to predict the evapotranspiration from a grass reference crop.

Fertigation — The application of fertilizer to the field by mixing the fertilizer with the water applied by the irrigation system.

Flexibility factor — A factor used in sizing irrigation projects that is used to provide management flexibility by increasing the capacity of the system beyond that required to only meet crop needs.

Fraction of growing season (F_S) — The amount of time that has elapsed since planting, or early growth, relative to the amount of time between planting and physiological maturity or dormancy.

Freeze protection — The use of irrigation to prevent crops from injury when the ambient air temperature drops below a critical level where damage occurs.

Frost protection — The use of irrigation to prevent crops from injury on clear, calm, cool nights when radiation from the crop would cool plants below a critical temperature where damage occurs.

Gross irrigation water requirement (F_g) — The net irrigation water requirement divided by the irrigation efficiency. Sometimes called irrigation requirement.

Gross system capacity (C_g) — The volume flow rate per unit land area (gallons per minute per acre) that the irrigation system is capable of supplying if it operates continuously.

Growing degree days (GDD) A temperature based system to describe the rate of plant growth. The growing degree day equals the difference in average daily air temperature and some base temperature where growth begins. The average air temperature is often limited by a maximum and minimum temperature.

Heat of vaporization (λ) The amount of energy required to evaporate a unit of water.

Irrigation scheduling A process that is repetitively used during the growing season to decide when to irrigate and how much water to apply.

Irrigation efficiency (E_i) The ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied, expressed as a percentage.

Irrigation water management Managing water, soil, and plant resources to optimize precipitation and applied irrigation water according to plant water needs. This includes:

- Applying the correct amount of water at the proper time (irrigation scheduling) without significant soil erosion and translocation of applied water
- Applying the predetermined amount of water (includes measurement)
- Adjusting irrigation system operations to maximize irrigation application uniformity
- Performing necessary irrigation system maintenance

Irrigation water requirement The quantity, or depth, of water in addition to precipitation, required to obtain desired crop yield and to maintain a salt balance in the root zone.

Langley The amount of energy (calories) received on a unit surface area (cm^2). This unit is commonly used for recording the amount of solar radiation received on a daily basis.

Latest irrigation date The latest date an irrigation can be started on a field to ensure that the soil water does not drop below the allowable depletion any where in the field before the irrigation is completed.

Leaching The process of water movement through and below the crop root zone by gravitation. It occurs whenever the infiltrated irrigation water and rainfall exceed ET_c and the water storage capacity of the soil profile.

Leaching fraction (L_f) That portion of the irrigation water and precipitation entering the soil that effectively flows through and below the crop root zone.

Leaching requirement (L_r) That part of the irrigation water and precipitation entering the soil that effectively must flow through and below the crop root zone to prevent the buildup of salinity within the crop root zone. Minimum leaching fraction needed to prevent yield reduction.

Leaf Area Index (LAI) The ratio of the amount of leaf area of a crop stand relative to the amount of land area underlying that crop.

Localized irrigation Irrigation systems which wet, in particular, the area of soil at the base of the plant. Encompassing term used to describe other irrigation systems such as: trickle, drip, drop, daily flow, micro.

Log-normal distribution A statistical distribution where the logarithms of data are normally distributed. The distribution is used to represent data that are positive and where values smaller than the mean occur more frequently than values bigger than the mean.

Longwave radiation Radiation that is due to the temperature differences between two objects. It occurs in the wavelength band between 3 to 70 microns.

Lysimeters Devices used to directly measure the rate of water use by crops. Usually a box is filled with soil and placed in the field. Plants are grown in the box. The change in water content in the box is monitored over time. The water loss is used to determine the evapotranspiration.

Management Allowed Depletion (MAD) The desired soil water deficit, below field capacity, at the time of irrigation.

Moisture retention curve The relationship between the amount of water remaining in the soil at equilibrium as a function of the matric potential. It is also known as soil-moisture characteristic curve.

Net irrigation requirement (F_n) The depth of irrigation water, exclusive of effective precipitation, stored soil moisture, or ground water that is required for meeting crop evapotranspiration for crop production and other related uses. Such uses may include water required for leaching, frost protection.

Net outgoing longwave radiation (R_b) The longwave radiation that is lost from the crop and soil system to the atmosphere.

Net radiation (R_n) The radiant energy available for crop ET. It is the portion of the intercepted incoming solar radiation minus the net outgoing longwave radiation.

Net system capacity (C_n) The volume flow rate per unit land area (gallons per minute per acre) required to supply water fast enough to satisfy crop water use without unintentional stress.

Osmotic effect The force a plant must exert to extract water from the soil. The presence of salt in the soil-water increases the force the plant must exert.

Osmotic potential The additional energy required to extract and absorb water from a salty soil.

Pan coefficient (k_p) A coefficient used to relate the rate of evaporation from an evaporation pan to the evapotranspiration for a grass reference crop.

Peak ET The maximum ET rate during the growing season. This rate is commonly used to design irrigation systems.

Penman-Monteith method A method used to predict the reference crop evapotranspiration using climatic data for: air temperature, relative humidity, wind speed, and solar radiation.

Percent downtime (D_t) The fraction of the total possible operating time that the irrigation system is shutoff. Downtime may result from equipment breakdown, electrical load management, farming needs, or other factors.

Persistence factor (P_f) A factor to represent the cumulative amount of evaporation from a wet soil following an irrigation or rain.

Psychrometric constant (γ) The change in vapor pressure of the air when it is cooled from the ambient temperature to the wet bulb temperature without adding or removing energy.

Radiation based ET_o method A method based primarily on radiation for predicting the evapotranspiration of a grass reference crop.

Reference crop evapotranspiration (ET_o) The evapotranspiration from a thick, healthy, well maintained grass that does not suffer any water stress. The reference crop ET_o is used to represent the water use of a standard crop in that environment even though that crop may not be physically grown in the area.

Relative humidity (RH) Ratio of the amount of water present in the air to the amount required for saturation of the air at the same dry bulb temperature and barometric pressure, expressed as a percentage.

Relative yield (Y_r) The ratio of the actual yield relative to the maximum attainable yield if no water or salinity stress occurs.

Root zone The area of the soil from which the crop roots extract water and nutrients.

Rotational area (A_t) The area that can be irrigated with a water supply if the water supply is furnished continuously.

Rotational delivery systems An irrigation water delivery system where water is furnished on a fixed cycle. An irrigator would receive water once during this cycle interval.

Salinity profile The diagrammatic representation of zones of varying levels of salinity, as exposed in a cut section of a field.

Salt tolerance threshold The electrical conductivity of the saturated-soil extract at which the yield of the respective crop begins to decline due to stress from salinity, expressed in mmho/cm.

Saturated vapor pressure (e^o) The vapor pressure when the air is completely saturated with water vapor so that no further evaporation can occur.

Sodium Adsorption Ratio (SAR) The ratio for soil extracts and irrigation water used to express the relative activity of sodium ions in exchange reactions with soil; expressed in meq/L.

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}}$$

Soil heat flux (G) The transfer of energy from (or to) the plant canopy to (or from) the soil.

Soil solution The aqueous solution existing in equilibrium with a soil at a particular soil water tension.

Soil-water balance A procedure to record the additions and withdrawals of water from the crop root zone and to determine the amount of available water remaining in the root zone at a desired time.

Soil-water potential The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation, at atmospheric pressure, to the soil-water at the point under consideration. The total soil-water potential is the sum of gravitational, matric, and osmotic potentials.

Solar radiation (R_s) Radiation from the sun that passes through the atmosphere and reaches the combined crop and soil surface. The energy is generally in a waveband width of 0.1 to 5 microns.

Specific heat (C_p) The amount of energy required to raise the temperature of an object one degree.

Stress factor (K_s) A factor used to modify the crop coefficient when water stress reduces the ability of the plant to transpire.

System capacity curve for conveyance systems A curve used to show the required flow rate in a system as a function of the size of the area to be irrigated.

Vapor pressure (e) The portion of the barometric pressure that is due to water vapor in the air.

Yield decline The amount of yield reduction per unit increase of salinity of the saturated-soil extract, expressed as percent yield reduction per mmho/cm.

Weibull distribution A statistical distribution used to represent data that are positive and that have a distribution that is skewed to the left of the mean value. The distribution is often used to evaluate the design probability for system capacity design.

Symbols

Symbols used for units:

ac	acres	hr	hours	mg	milligram
ft^3/s	cubic feet per second	in	inches	mi	miles
cc	cubic contimenters	L	liters	min	minutes
cm	centimeters	lang	langleys	mmho	millimhos
d	days	lb	pounds	mo	month
ds	decisiemens	m	meters	ppm	parts per million
ft	feet	mb	millibars	psi	pounds per square inch
g	grams	meq	milliequivalents	s	seconds
gpm	gallons per minute				

Symbol	Definition	Units
α	albedo of crop and soil surface	
α_d	distribution uniformity	%
β	Bowen ratio	
γ	psychrometric constant	mb/°F
γ^*	adjusted psychrometric constant = $\gamma (1 + r_c / r_a)$	
Δ	slope of the saturated vapor pressure curve	mb/°F
Δt	length of time in a period	hr or d
ΔT	air temperature reduction for crop cooling	°F
η	exponent in Brooks Corey hydraulic conductivity function	
θ_v	volumetric water content	%
θ_r	residual soil water content	%
θ_s	saturated volumetric water content	%
θ_m	solar altitude at solar noon	degrees
θ_d	solar declinitation angle	degrees
θ_{fc}	volumetric water content at field capacity	%
θ_{pwp}	volumetric water content at permanent wilting point	%
ε'	atmospheric emittance	
λ	heat of vaporization	lang/in
λ_p	pore size distribution index	
ρ	density of air	lb/ft^3
ρ_b	soil bulk density.	lb/ft^3
ρ_s	specific gravity of soil particles (about 2.65)	
ρ_w	density of water equal to 62.4	lb/ft^3
σ	Stephan-Boltzman constant	
ϕ	soil porosity	
ϕ_e	effective porosity	
A	leading parameter of clear sky radiation equation	
a	empirical slope in longwave radiation equation	
a_1	factor to account for effect of day length on emissivity	
A_d	advection.	lang/d
A_f	average wet soil evaporation factor	
A_H	energy used to heat air.	lang/d
A_h	air heat flux.	lang/d
A_i	irrigated area	ac
AELH	application efficiency of low-half	%

AELQ	application efficiency of low-quarter	%
AR	advance ratio for surface irrigation	
ASW	percentage of total available soil water stored in root zone	%
ASW_c	critical value of ASW	%
A_t	rotational irrigated area	ac
AW	available soil water	in
AWC	available water content	%
a_t	intercept for FAO Blaney-Criddle ET_o method	
A_u	fraction of the field that is under irrigated	%
B	cosine coefficient in clear sky radiation equation	
b	empirical intercept for longwave radiation equation.	
b_n	parameter to compute value of b_r using n/N and RH_{min}	
BP	barometric pressure	mb
b_r	slope term in Radiation ET_o method	
b_t	slope for the FAO Blaney-Criddle ET_o method	
b_u	parameter to compute value of br using U_d and RH_{min}	
C_1	coefficient to convert energy units into water use	
C_e	adjustment factor for the FAO Blaney-Criddle ET_o method	
C_f	farm capacity	gpm/ac or in/d
C_g	gross system capacity	gpm/ac or in/d
C_H	energy used to heat crop	lang/d
C_n	net system capacity	gpm/ac or in/d
c_p	specific heat of dry air	lang/in-°F
c_s	empirical specific heat coefficient for soil	lang/°F/d
CU	Christiansen's coefficient of uniformity	
CV	coefficient of variation	
d	zero plane displacement height	ft
D	usable soil water storage	in
D_a	depth of infiltrated water including irrigation and precipitation	in
D_d	depth of drainage water per unit land area.	in
DOY	day of the year (1-365)	
D_p	deep percolation	in
D_{pf}	deep percolation from irrigation	in
D_{pr}	deep percolation from rainfall	in
D_t	percent downtime	%
DU	distribution uniformity of an irrigation application	
d_w	distance from bottom of the root zone to water table	ft
e	actual vapor pressure.	mb
e°	saturated vapor pressure of air	
$e^o_{T_{max\,z}}$	saturated vapor pressure at maximum air temperature	mb
$e^o_{T_{min\,z}}$	saturated vapor pressure at minimum air temperature	mb
e^o_w	saturated vapor pressure at the wet bulb temperature	mb
e^o_z	average saturated vapor pressure at height z above the soil surface	mb
e_d	saturated vapor pressure at dew point	
e_z	actual vapor pressure at height z above the soil surface	
E_a	application efficiency	%
E_b	on-farm canal conveyance efficiency	%
EC^*_d	maximum value of electrical conductivity of the drainage water without reducing crop yield	mmho/cm
E_c	conveyance efficiency	%

EC_{aw}	electrical conductivity of the applied water	mmho/cm
EC_d	electrical conductivity of the drainage water	mmho/cm
EC_e	electrical conductivity of the saturated-soil extract	mmho/cm
EC_i	electrical conductivity of the irrigation water	mmho/cm
EC_t	electrical conductivity where yield reduction begins	mmho/cm
EC_y	electrical conductivity above which the yield is zero	mmho/cm
E_d	efficiency of the irrigation project distribution system	%
E_{et}	energy available for evapotranspiration	
E_f	combined on-farm conveyance and application efficiency	%
E_h	application efficiency of the low-half	%
E_i	irrigation efficiency	
E_I	net energy input	lang/d
E_{lev}	elevation above sea level	ft
E_{os}	average surface evaporation in the non-growing season	in
E_{pan}	evaporation from class A pan	in/d
E_q	application efficiency of the low-quarter	%
ESP	exchangable sodium percentage	%
ET	crop evapotranspiration during a period	in
ET_c	actual crop water use, or evapotranspiration	in or in/d
ET_d	average daily peak ET for the period analyzed	in/d
ET_m	peak monthly ET rate	in
ET_o	reference ET for 5 inch tall clipped grass	in/d
E_{ws}	total wet soil evaporation for a wetting event	in
EXP	exponential function	
EC_w	electrical conductivity of the water	mmho/cm
f	irrigation frequency	d^{-1}
f_p	interval between significant rains or irrigations	d
f(t)	wet soil surface evaporation decay function	
F	irrigation amount during a period	in
F_g	gross irrigation requirement	in
F'_g	gross irrigation requirement to meet the salinity requirement	in
F_i	irrigation depth that must infiltrate if all infiltrated precipitation contributes to crop evapotranspiration	in
F_n	net irrigation	in
F_{ro}	fraction of the gross irrigation that does not infiltrate	
F_S	fraction of growing season	
F_{S1}	fraction of growing season at end of initial crop growth stage	
F_{S2}	fraction of growing season at end of canopy development stage	
F_{S3}	fraction of growing season at end of mid-season growth stage	
F_w	fraction of the soil surface wetted	
G	soil heat flux.	lang/d
GDD	cumulative growing degree days after planting	
GDD_i	cumulative growing degree days on day i	°F
GDD_m	cumulative growing degree days needed for maturity	°F
GW	ground water contribution to ET during a period.	in
h	capillary pressure head	in
h_b	capillary pressure head at the bubbling pressure	
h_c	height of the crop	in
H_r	hours of water delivery per day	
h_w	height of ground cover at the weather station	in
I_f	intake family	

k	von Karman's constant 0.41	
k_p	pan coefficient.	
K	hydraulic conductivity	in/d
K_1	unit conversion constant for Penman-Monteith equation	
K_a	average crop coefficient	
K_c	crop coefficient	
K_{cb}	basal crop coefficient	
K_{cm}	value of basal crop coefficient at crop maturity	
K_{cp}	peak or maximum value of basal crop coefficient	
K_O	saturated conductivity	in/d
K_s	stress factor to reduce water use for stressed crops	
K_w	factor to account for increased evaporation from wet soils	
LAI	leaf area index	
Lat	latitude N	degrees
LN	natural logarithm	
LOG	base 10 logarithm	
L_f	leaching fraction for steady state conditions	
L_r	leaching requirement	
m	rank of an ET value (m=1 for the smallest value)	
M	month of the year (1 to 12).	
n	Mannings roughness coefficient	
n	number of years analyzed.	
n/N	ratio of actual (n) to maximum possible sunshine hrs (N)	
N_d	day of the month (1 to 31)	
p	monthly percent of annual daytime hours	%
pH	concentration of hydrogen ions	
P	precipitation or rainfall during a period	in
P_a	average annual precipitation	in
P_b	probability that ET_c will be less than a specified value	%
P_e	average monthly effective monthly precipitation	in
P_f	wet soil evaporation persistence factor	
P_{net}	net annual rainfall that contributes to leaching	in
P_s	energy used for photosynthesis	lang/d
P_t	total mean monthly precipitation	in
q	soil water flux (volume of water flow per unit area)	in/hr
q_r	relative rate of upward water flow	
q_u	rate of upward flow	in/d
Q	system capacity flow rate	ft^3/s or gpm
Q_t	delivery flow rate	ft^3/s
Q_{max}	maximum nonerosive furrow inflow	
r_a	aerodynamic resistance to sensible heat and vapor transfer	d/mi
r_c	surface resistance to vapor transport	d/mi
R_a	extraterrestrial radiation	lang/d
R_b	net outgoing longwave radiation	lang/d
R_{bo}	net outgoing longwave radiation on a clear day	lang/d
R_d	root zone depth	in
R_e	portion of applied water that reaches the soil or canopy	
R_f	surface runoff during the period	in
R_f	recurrence interval for soil surface wetting	d
RH	relative humidity	%
RH_a	long-term average relative humidity for a time period	%

RH_{min}	mean minimum relative humidity	%
R_n	net radiation	lang/d
RO	runoff	in
RO_f	runoff from irrigation	in
RO_r	runoff from rainfall	in
R_r	reflected radiation	lang/d
R_s	incoming solar radiation	lang/d
R_{so}	amount of incident solar radiation on a clear day	lang/d
R^e_{so}	clear sky radiation correction term for elevation	lang/d
R^o_{so}	clear sky radiation at sea level	lang/d
SAR	sodium absorption ratio	
SD_L	Spray and drift losses from irrigation water in air and off plant canopies	in
S_e	effective saturation	
SF	soil water storage factor	
S_f	soil heat flux	lang/d
S_g	stage of crop growth.	
S_H	energy used to heat soil	lang/d
SIN	sine function expressed in degrees	
SMD	soil moisture deficit	in
S_o	field slope or grade	ft/ft
SP_a	average annual surface runoff from precipitation	in
SW	soil water in the crop root zone	in
SW_b	soil water in the root zone at the beginning of a period	in
SW_e	soil water in the root zone at the end of a period	in
ΔSW	change in soil water	in
T	mean air temperature for the period	°F
t	elapsed time since wetting	d
T_a	average air temperature for the current day	°F
T_{ai}	average air temperature on day i	°F
TAW	total available water	in
T_{base}	base temperature at which photosynthesis and growth begins	°F
t_d	time required for the soil surface to dry	d
T_d	dew point temperature	°F
TDS	total dissolved solids	mg/L
t_i	duration of an individual irrigation	d
T_{max}	daily maximum temperature	
T_{maxk}	maximum daily absolute air temperature	°K
T_{min}	daily minimum temperature	
T_{mink}	minimum daily absolute air temperature	°K
T_n	time required to infiltrate the net depth F_n	hr
T_p	mean air temperature for the preceding three days	°F
T_s	effective absolute temperature of the earths surface	°K
T_s^4	effective temperature of earth surface	
T_t	time required for water to advance across the field	hr
T_w	wet bulb temperature	°F
U	wind velocity, or daily wind run	mi/hr or mi/d
U*	representative friction velocity	
U_1	measured wind speed at height Z_1	mi/hr
U_2	estimated wind speed at height Z_2.	mi/hr
U_{2m}	daily wind run at 2 meter height	mi/d

U_{3m}	daily wind run at 3 meter height	mi/d
U_c	wind speed at height Z over the reference crop	mi/d
U_d	daytime wind speed	mi/hr, mi/d
U_f	adjustment factor for wind speed	
U_r	ratio of daytime to nighttime wind speeds.	
U_w	wind speed	mi/d
U_z	daily wind run at height z	mi/d
W	Weibull transform of P_b	
W_u	average peak water use rate	gpm/ac
Y_d	relative yield decrease per unit of salinity increase	%/mmho/cm
Y_r	relative crop yield	
z	distance below the soil surface	
Z	height above the soil surface	ft
Z_o	roughness parameter	ft
Z_{om}	roughness length for momentum transfer.	ft
Z_{ov}	roughness length for vapor transfer	ft
Z_p	height of temperature and humidity probe	ft
Z_w	height of the anemometer at the weather station	ft

Index

A

Adequacy of irrigation 2–170
Advection 2–6, 2–7, 2–8, 2–38, 2–39, 2–40, 2–41, 2–267, 2–268, 2–275
Aerodynamic resistance 2–44, 2–46, 2–47, 2–278
Albedo 2–5, 2–6, 2–22, 2–23, 2–29, 2–267, 2–275
Application efficiency 2–116, 2–118, 2–125, 2–168, 2–169, 2–171, 2–172, 2–173, 2–174, 2–175, 2–178, 2–179, 2–180, 2–183, 2–187, 2–194, 2–195, 2–206, 2–214, 2–217, 2–218, 2–222, 2–267, 2–276
Application Efficiency Low Half 2–172, 2–173
Application Efficiency Low Quarter 2–168, 2–172, 2–173
Average crop coefficient 2–88, 2–89, 2–90, 2–91, 2–188, 2–267, 2–278

B

Barometric pressure 2–6, 2–13, 2–44, 2–182, 2–267, 2–272, 2–273, 2–276
Basal crop coefficient 2–67 – 2–80, 2–84, 2–85, 2–88, 2–89, 2–97, 2–187, 2–267, 2–278
Blaney-Criddle 2–12, 2–41, 2–42, 2–56, 2–57, 2–227, 2–230, 2–233, 2–269, 2–276
Bubbling pressure 2–155, 2–157, 2–161, 2–163, 2–277

C

Canopy resistance 2–46
Capillary pressure 2–155, 2–157, 2–162, 2–277
Chemigation 2–133, 2–139, 2–140, 2–267
Clear sky radiation 2–24, 2–25, 2–26, 2–27, 2–275
Coefficient of uniformity 2–139, 2–167, 2–168, 2–173, 2–174, 2–267, 2–276
Conveyance 2–4, 2–164, 2–165, 2–166, 2–181, 2–182, 2–183, 2–184, 2–185, 2–195, 2–196, 2–221, 2–222, 2–224, 2–225, 2–226, 2–268, 2–273, 2–276, 2–277
Conveyance efficiency 2–164, 2–181, 2–182, 2–183, 2–184, 2–195, 2–221, 2–222, 2–224, 2–268, 2–276
Critical temperature 2–133, 2–137, 2–269
Crop coefficient 2–3, 2–11, 2–12, 2–63, 2–65, 2–66, 2–67, 2–68, 2–69, 2–70, 2–71, 2–72, 2–73, 2–77, 2–78, 2–79, 2–80, 2–81, 2–84, 2–85, 2–87, 2–88, 2–89, 2–90, 2–91, 2–92, 2–97, 2–187, 2–188, 2–199, 2–227, 2–230, 2–267, 2–268, 2–273, 2–278
Crop cooling 2–164, 2–275
Crop evapotranspiration 2–1, 2–3, 2–7, 2–8, 2–9, 2–11, 2–13, 2–16, 2–17, 2–18, 2–41, 2–42, 2–48, 2–53, 2–63, 2–66, 2–69, 2–84, 2–85, 2–91, 2–97, 2–98, 2–115, 2–116, 2–125, 2–142, 2–144, 2–145, 2–147, 2–148, 2–155, 2–164, 2–187, 2–188, 2–192, 2–193, 2–199, 2–205, 2–209, 2–269, 2–271, 2–277
Crop salt tolerance 2–104, 2–115, 2–116, 2–123, 2–126
Cycle time 2–209, 2–212, 2–214, 2–268

D

Day of year 2–56, 2–259
Deep percolation 2–2, 2–8, 2–9, 2–119, 2–135, 2–142, 2–145, 2–146, 2–164, 2–165, 2–166, 2–169, 2–172, 2–181, 2–225, 2–268, 2–276
Delivery schedule 2–184, 2–185, 2–216, 2–217, 2–219, 2–220, 2–223, 2–224
Dew point 2–13, 2–14, 2–15, 2–16, 2–28, 2–30, 2–46, 2–133, 2–134, 2–268, 2–279

E

Effective cover date 2–66, 2–268
Effective precipitation 2–3, 2–119, 2–120, 2–142, 2–144, 2–145, 2–146, 2–147, 2–148, 2–149, 2–150, 2–152, 2–153, 2–154, 2–187, 2–189, 2–268, 2–271
Electrical conductivity 2–98, 2–101, 2–102, 2–104, 2–115, 2–116, 2–117, 2–119, 2–120, 2–190, 2–268, 2–269, 2–277
Elevation 2–9, 2–13, 2–18, 2–24, 2–25, 2–27, 2–45, 2–48, 2–56, 2–57, 2–125, 2–128, 2–157, 2–166, 2–167, 2–180, 2–273, 2–277, 2–279
Emittance 2–25, 2–28, 2–31, 2–269, 2–275
Erosion control 2–133, 2–138
Evaporation pan 2–39, 2–41, 2–43, 2–62, 2–63, 2–64, 2–65, 2–199, 2–269, 2–271
Evapotranspiration 2–1, 2–4 – 2–8, 2–11, 2–13, 2–16, 2–20, 2–34, 2–37, 2–38, 2–40, 2–41 – 2–44, 2–56, 2–62, 2–66, 2–68, 2–73, 2–82, 2–83, 2–84, 2–88, 2–91, 2–92, 2–97, 2–116, 2–118, 2–119, 2–123, 2–133, 2–142, 2–144, 2–145, 2–147 – 2–150, 2–155, 2–164, 2–187, 2–188, 2–192, 2–193, 2–197, 2–199, 2–202, 2–205, 2–220, 2–231, 2–261, 2–267, 2–268, 2–269, 2–271, 2–272, 2–277
Exchangeable sodium 2–99, 2–128, 2–131, 2–132, 2–269
Extraterrestrial radiation 2–5, 2–32, 2–33, 2–34, 2–278

F

Flexibility factor 2–220, 2–222, 2–224, 2–269
Fraction of growing season 2–71, 2–94, 2–96, 2–269, 2–277
Freeze protection 2–134, 2–269
Frost protection 2–133 – 2–137, 2–269, 2–271

G

Gross irrigation 2–2, 2–116, 2–118, 2–119, 2–120, 2–122, 2–146, 2–189, 2–190, 2–193, 2–194, 2–209, 2–217, 2–218, 2–219, 2–269, 2–277
Ground water 2–2, 2–8, 2–115, 2–123, 2–128, 2–140, 2–144, 2–146, 2–147, 2–166, 2–169, 2–170, 2–181, 2–187, 2–226, 2–227, 2–271, 2–277
Growing degree days 2–68, 2–92, 2–93, 2–94, 2–95, 2–96, 2–270, 2–277

H

Heat of vaporization 2–17, 2–44, 2–52, 2–270, 2–275
Hydraulic conductivity 2–124, 2–128, 2–131, 2–132, 2–155, 2–157, 2–161, 2–163, 2–182, 2–275, 2–278

I

Infiltration 2–98, 2–99, 2–100, 2–116, 2–128, 2–129, 2–132, 2–140, 2–142, 2–145, 2–146, 2–147, 2–165 – 2–169, 2–180
Irrigation efficiency 2–3, 2–121, 2–164, 2–181, 2–194, 2–220, 2–269
Irrigation scheduling 2–1, 2–2, 2–11, 2–12, 2–34, 2–43, 2–68, 2–69, 2–78, 2–92, 2–94, 2–116, 2–144, 2–146, 2–147, 2–164, 2–166, 2–168, 2–208, 2–209, 2–214, 2–215, 2–224, 2–270
Irrigation water requirement 2–1, 2–3, 2–4, 2–66, 2–82, 2–97, 2–133, 2–142, 2–150, 2–154, 2–213, 2–216, 2–220, 2–224, 2–269, 2–270

L

Latitude 2–5, 2–13, 2–22 – 2–26, 2–29, 2–32, 2–56, 2–57, 2–227, 2–228, 2–229, 2–233, 2–234, 2–278
Leaching fraction 2–102, 2–105, 2–115, 2–116, 2–123, 2–142, 2–270
Leaching requirement 2–3, 2–98, 2–101, 2–115, 2–116, 2–117, 2–118, 2–120, 2–121, 2–122, 2–124, 2–126, 2–133, 2–154, 2–190, 2–194, 2–225, 2–270, 2–278
Log-normal 2–150, 2–198, 2–201, 2–202, 2–270
Longwave radiation 2–6, 2–7, 2–22, 2–23, 2–24, 2–25, 2–28, 2–29, 2–31, 2–136, 2–269, 2–270, 2–271, 2–275
Lysimeter 2–9, 2–10, 2–52, 2–271

M

Management allowed depletion 2–2
Moisture retention curve 2–271

N

Net irrigation 2–8, 2–115, 2–116, 2–117, 2–144, 2–146, 2–148, 2–154, 2–187, 2–189, 2–200, 2–205, 2–208, 2–213, 2–220, 2–269, 2–271, 2–277
Net radiation 2–6, 2–7, 2–8, 2–22, 2–28, 2–29, 2–34, 2–35, 2–44, 2–46, 2–271, 2–279

P

Pan coefficient 2–62, 2–63, 2–64, 2–65, 2–199, 2–271, 2–278
Peak ET 2–197, 2–198, 2–199, 2–202, 2–271, 2–277
Penman-Monteith 2–41, 2–42, 2–43, 2–46, 2–48 – 2–51, 2–53, 2–64, 2–65, 2–78, 2–97, 2–271, 2–278
Persistence factor 2–85, 2–86, 2–87, 2–271, 2–278
Pore size distribution index 2–155, 2–157, 2–161, 2–275
Precipitation 2–1, 2–2, 2–10, 2–115, 2–116, 2–119, 2–120, 2–123, 2–142, 2–143, 2–144, 2–146, 2–147, 2–148, 2–150, 2–152, 2–153, 2–187, 2–189, 2–225, 2–227, 2–268, 2–269, 2–270, 2–276, 2–277, 2–278
Project water requirements 2–216
Psychrometric 2–17, 2–44, 2–52, 2–272, 2–275

R

Radiation method 2–41, 2–42, 2–43, 2–52, 2–53, 2–54, 2–57
Reclamation 2–129, 2–131, 2–132, 2–220
Reference crop 2–3, 2–11, 2–12, 2–13, 2–16, 2–22, 2–41, 2–46, 2–48, 2–52, 2–53, 2–62, 2–63, 2–66, 2–69, 2–73, 2–77 – 2–81, 2–84, 2–91, 2–97, 2–227, 2–267, 2–268, 2–269, 2–271, 2–272
Relative crop yield 2–105, 2–280
Relative humidity 2–6, 2–14, 2–15, 2–41, 2–43, 2–47, 2–52, 2–54, 2–56, 2–57, 2–62, 2–63, 2–70, 2–135, 2–136, 2–138, 2–144, 2–165, 2–231, 2–268, 2–271, 2–272, 2–278
Rotational area 2–185, 2–218, 2–272
Roughness 2–18, 2–44, 2–46, 2–144, 2–165, 2–175, 2–177, 2–280
Runoff 2–2, 2–8, 2–9, 2–118, 2–119, 2–120, 2–124, 2–125, 2–129, 2–135, 2–138, 2–140, 2–142, 2–145, 2–146, 2–164, 2–165, 2–166, 2–168, 2–169, 2–171, 2–172, 2–173, 2–175, 2–177, 2–180, 2–190, 2–193, 2–194, 2–225, 2–268, 2–278, 2–279

S

Salinity 2–41, 2–98, 2–99 – 2–102, 2–104, 2–105, 2–110, 2–111, 2–115, 2–116, 2–117, 2–119, 2–120, 2–123 – 2–126, 2–128, 2–129, 2–133, 2–142, 2–155, 2–187, 2–192, 2–193, 2–226, 2–270, 2–272, 2–273, 2–280
Salinity control 2–98, 2–115, 2–120, 2–122, 2–125, 2–190, 2–191, 2–194
Salt balance 2–1, 2–115, 2–116, 2–119, 2–123, 2–270
Salt tolerance threshold 2–110, 2–116, 2–121, 2–190, 2–272
Saturated-soil extract 2–98, 2–99, 2–101, 2–104, 2–111, 2–115, 2–116, 2–272, 2–273, 2–277
Saturation 2–28, 2–102, 2–155, 2–162, 2–163, 2–268, 2–269, 2–272, 2–279
Seasonal irrigation requirement 2–119, 2–187, 2–188, 2–189, 2–190, 2–191, 2–193, 2–194, 2–208
Sodium Absorption Ratio 2–99, 2–279
Soil heat flux 2–7, 2–34, 2–36, 2–37, 2–44, 2–272, 2–277, 2–279
Soil water balance 2–1, 2–2, 2–8, 2–9, 2–146, 2–187, 2–194, 2–202, 2–207, 2–209, 2–264
Soil water potential 2–137, 2–155, 2–213
Solar radiation 2–5, 2–6, 2–22, 2–24, 2–32, 2–34, 2–41, 2–43, 2–46, 2–52, 2–267, 2–271, 2–273, 2–279
Specific ion effects 2–104, 2–111
Stage of growth 2–1, 2–66, 2–70, 2–94, 2–96, 2–144, 2–165, 2–232
Stress factor 2–68, 2–82, 2–84, 2–88, 2–213, 2–273, 2–278
Sunshine 2–13, 2–32, 2–56, 2–58, 2–59, 2–231, 2–278
System capacity 2–154, 2–194, 2–197, 2–202, 2–206 – 2–209, 2–214, 2–216, 2–218, 2–220 – 2–224, 2–269, 2–271, 2–273, 2–276

T

Total available water 2–2, 2–82, 2–84

U

Uniformity 2–123, 2–124, 2–135, 2–139, 2–140, 2–164 – 2–169, 2–171 – 2–174, 2–267, 2–268, 2–275, 2–276
Upward flow 2–115, 2–116, 2–123, 2–147, 2–155, 2–157, 2–158, 2–161, 2–163, 2–189, 2–278

V

Vapor pressure 2–6, 2–14 – 2–17, 2–28, 2–30, 2–44, 2–46, 2–52, 2–272, 2–273, 2–275, 2–276
Vapor pressure deficit 2–15, 2–16, 2–37, 2–57, 2–165, 2–168
Volumetric water content 2–82, 2–84, 2–155, 2–162, 2–275

W

Water conservation 2–225, 2–226
Water table 2–3, 2–8, 2–9, 2–115, 2–123, 2–125, 2–128, 2–130, 2–144, 2–155, 2–157, 2–158, 2–159, 2–160, 2–161, 2–166, 2–180, 2–182, 2–187, 2–276
Weather station 2–13, 2–15, 2–18, 2–19, 2–20, 2–37, 2–43, 2–46, 2–47, 2–48, 2–277
Weibull distribution 2–198, 2–200, 2–273
Wet soil evaporation 2–68, 2–85 – 2–89, 2–275, 2–277, 2–278
Wind run 2–13, 2–20, 2–21, 2–44, 2–46, 2–47, 2–53, 2–63, 2–70, 2–73, 2–279

Y

Yield decline 2–110, 2–273

Z

Zero plane displacement 2–18, 2–276

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Section 15

IRRIGATION

Chapter 3

PLANNING FARM IRRIGATION SYSTEMS

Soil Conservation Service
United States Department of Agriculture

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 3--PLANNING FARM IRRIGATION SYSTEMS

Contents

	Page
Introduction	3-1
Proper planning permits conservation irrigation	3-1
Preliminary considerations	3-3
What the irrigator should know	3-3
What the planner should know	3-3
Planning procedure	3-4
Select method	3-4
Layout	3-4
Application	3-5
Delivery	3-5
Disposal	3-5
Factors in planning	3-5
Soils	3-5
Intake rates	3-6
Water-holding capacity	3-6
Depth	3-6
Other characteristics	3-6
Drainage	3-7
Erosion	3-8
Saline or alkali conditions	3-9
Topography	3-10
Sprinkler irrigation	3-11
Surface irrigation	3-11
Subirrigation	3-11
Supply lines	3-11
Conservation practices	3-12
Water supply	3-12
Water rights	3-12
Quantity	3-13
Quality	3-14
Type of supply	3-15
Location of supply	3-24
Climate	3-25
Precipitation	3-25
Temperature	3-26

Page

Farm enterprise..... 3-26
Crops..... 3-26
Labor..... 3-27
Field arrangement..... 3-27
Farm equipment available..... 3-27
Available power..... 3-28
Existing facilities..... 3-28
Field road system..... 3-28
Finances..... 3-28
Physical features..... 3-28
Adapted methods of water application..... 3-29
Sprinkler irrigation..... 3-29
Sprinkler method..... 3-30
Surface irrigation..... 3-35
Graded-border method..... 3-35
Level-border (basin) method..... 3-36
Contour-levee method..... 3-37
Contour-ditch method..... 3-39
Graded-furrow method..... 3-40
Contour-furrow method..... 3-41
Level-furrow method..... 3-43
Corrugation method..... 3-44
Subirrigation..... 3-45
Subirrigation method..... 3-46
Irrigation water conveyance..... 3-47
Ditches..... 3-48
Unlined ditches..... 3-48
Lined ditches..... 3-49
Conveyance structures..... 3-54
Grade-control structures..... 3-57
Distribution-control structures..... 3-58
Application-control structures..... 3-62
Pipelines..... 3-73
Low-pressure pipelines..... 3-74
High-pressure pipelines..... 3-74
Inlet structures..... 3-77
Vents..... 3-78
Control structures..... 3-80
Outlets..... 3-83
Water disposal..... 3-87
Surface-water disposal..... 3-87
Effect of irrigation method..... 3-87
Design considerations..... 3-88
Subsurface-water disposal..... 3-88
Interceptor drains..... 3-88
Relief drains..... 3-88
Wells..... 3-88
Outlets..... 3-89
Water measurement..... 3-89

Page

Irrigation guides..... 3-90
Area covered..... 3-90
Content..... 3-90
Soils..... 3-90
Crops..... 3-90
Irrigation specifications..... 3-91
Use..... 3-91

FIGURES

Figure		Page
3-1	A farm irrigation system	3-2
3-2	Water loss in an irrigation reservoir	3-16
3-3	Off-stream storage reservoir	3-18
3-4	Ground-water storage reservoir	3-22
3-5	Regulating reservoir	3-22
3-6	Sprinkler irrigation	3-30
3-7	Hand-move sprinkler	3-31
3-8	Big-gun sprinkler	3-31
3-9	Rotating-boom sprinkler	3-32
3-10	Side-roll sprinkler	3-32
3-11	Two-lateral sprinkler	3-32
3-12	Self-propelled sprinkler	3-33
3-13	Solid-set sprinkler	3-33
3-14	Perforated-pipe sprinkler	3-33
3-15	Graded-border irrigation	3-35
3-16	Level-border irrigation	3-36
3-17	Contour-levee irrigation	3-38
3-18	Contour-ditch irrigation	3-39
3-19	Graded-furrow irrigation	3-40
3-20	Contour-furrow irrigation	3-42
3-21	Level-furrow irrigation	3-43
3-22	Corrugation irrigation	3-44
3-23	Subirrigation	3-46
3-24	Placing concrete ditch lining by slip-form method	3-51
3-25	Constructing concrete ditch lining by alternate-panel method	3-51
3-26	Timber-supported metal flume	3-56
3-27	Section of a concrete inverted siphon	3-57
3-28	Five drop structures	3-59
3-29	Headgate equipped to measure water directly from an irrigation canal to a farm ditch	3-60
3-30	Pump stilling basin and division box	3-61
3-31	Division box with four chambers	3-61
3-32	Combination drop and check	3-63
3-33	Portable plastic check	3-63
3-34	Portable canvas check	3-63

Figure		Page
3-35	Canvas check with adjustable sack outlet	3-64
3-36	Metal windless check	3-64
3-37	Adjustable metal check in a lined ditch	3-64
3-38	Permanent concrete check	3-65
3-39	Installing a metal check	3-65
3-40	Metal-pipe turnout in a lined ditch	3-66
3-41	Two-inch gate turnout	3-66
3-42	Concrete-block turnout in a lined ditch	3-67
3-43	Metal turnout	3-67
3-44	Turnout boxes in background	3-68
3-45	Concrete turnout with a flash board gate	3-68
3-46	Concrete-pipe turnout	3-69
3-47	Installing a concrete-pipe turnout	3-69
3-48	Two-inch siphon tubes irrigating furrows	3-71
3-49	Eight-inch siphon tubes irrigating a border	3-71
3-50	Large metal siphon and pump for priming	3-71
3-51	Gated pipe for furrow irrigation of corn	3-72
3-52	Closeup of gate in pipe	3-72
3-53	Flexible gated pipe; sacks prevent erosion and clothespins regulate flow	3-72
3-54	Installing plastic pipeline	3-75
3-55	Installing 15-inch concrete irrigation pipe	3-75
3-56	Removing inside form from concrete pipeline cast in place	3-76
3-57	Pouring concrete pipeline using sheet-metal slip form	3-76
3-58	Low-head open stand for concrete pipe	3-77
3-59	Capped high-head steel stand	3-77
3-60	Gravity inlet for buried low-pressure pipeline	3-79
3-61	Typical concrete-pipe sand trap	3-79
3-62	Typical trash screen	3-79
3-63	Desilting box and trash screen	3-79
3-64	Typical capped vent	3-81
3-65	Section of a capped vent	3-81
3-66	Closeup of air-release valve on right and alfalfa valve on left	3-81
3-67	Section of a concrete pipe gate stand used to control flow into two laterals	3-82
3-68	Section of concrete-pipe overflow stand	3-82
3-69	Concrete-pipe overflow stand	3-82
3-70	Section of a float-valve stand	3-84
3-71	Section of alfalfa valve mounted on concrete pipe	3-84
3-72	Hydrant attached to alfalfa valve for gated pipe	3-84
3-73	Section of an orchard valve	3-86
3-74	Orchard valve	3-86
3-75	Open-pot outlet with an orchard valve and slide-gate control	3-86
3-76	Section of capped riser or pot outlet	3-86
3-77	Irrigation guide for all irrigated sections of Kansas	3-92

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 3--PLANNING FARM IRRIGATION SYSTEMS

Introduction

Proper Planning Permits Conservation Irrigation

Conservation irrigation is the use of irrigated soils and irrigation water in a way that insures high production without wasting either water or soil. It means using cropping, irrigation, and cultural practices that maintain the land in permanent agriculture. To an irrigator conservation irrigation can mean saving water, controlling erosion, better crop yields, lower production costs, and continued productivity of his irrigated land.

One of the major factors in conservation irrigation is a properly planned conservation farm irrigation system. A conservation farm irrigation system is the complete arrangement of the delivery and application facilities needed to distribute irrigation water efficiently to all land served by the system.

A farm irrigation system consists of three parts--delivery, application, and disposal (fig. 1). The delivery part consists of the facilities needed to convey irrigation water from the source of supply to individual fields and includes supply ditches and pipelines, valves, hydrants, flumes, measuring devices, turnouts, and checks. For the application and distribution of water on a field, head ditches, distribution pipelines (buried or surface), valves and hydrants, gated pipe, siphon tubes, sprinkler lines, and sprinkler nozzles and equipment must be planned. Tail-water or collection ditches, sumps, and any other facilities needed to collect and safely dispose of, or recover for further irrigation, any waste water and storm runoff make up the disposal part of the system.

Few, if any, farm operating units have identical physical, economic, and managerial conditions. Careful and adequate planning is necessary if the irrigation system is to meet the requirements of the farm operating unit on which it is to be used. It must fit the soils, crops, climate, water supply, and farming operations. To be adequate, a system must have the capacity to meet the peak-use requirements of the crops to be grown (chap. 1) and to deliver water at the rate required for the irrigation method used. It should be planned and designed to operate at high efficiency to conserve irrigation water.

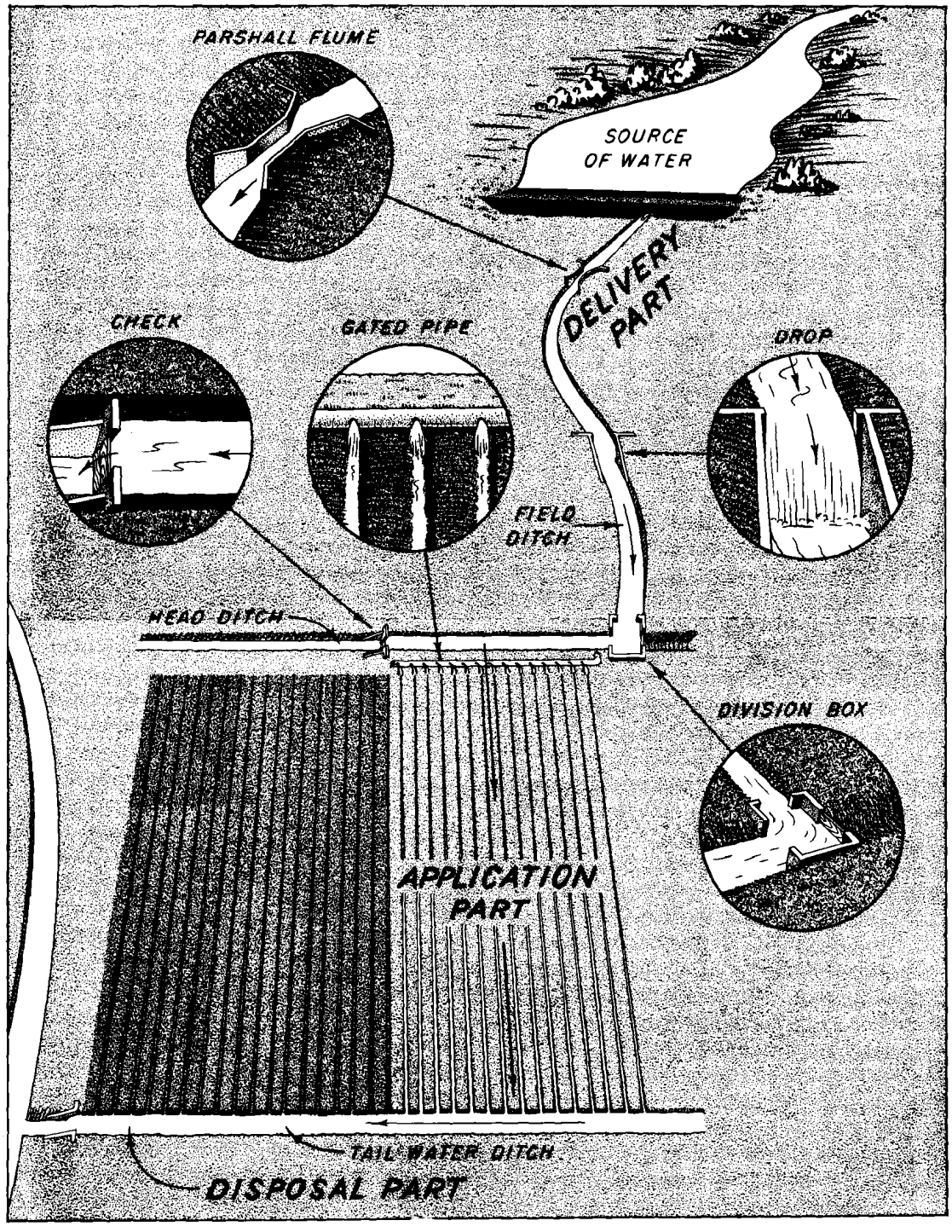


Figure 3-1.--A farm irrigation system.

Preliminary Considerations

For an irrigation system to function as planned both irrigator and planner must know and agree on some things before they spend much time in planning.

What the Irrigator Should Know

Conservation irrigation, like other farm operations, must be undertaken only if it can be done successfully and at a profit. In other words, the benefits from irrigation must increase farm income enough to cover all costs of purchasing, installing, operating, and maintaining the irrigation system and provide a reasonable return from the owner's investment.

Water is only one of several limiting factors in producing high yields of any crop. An irrigator should know the capability of his land under irrigation. He should know the soil management practices necessary to maintain good tilth and fertility. He should be willing to use the best adapted crop variety and the plant population that will produce the best yields and to have an adequate system for controlling plant diseases and insects. He should understand and be willing to practice irrigation water management.

Irrigation Water Management.--Conservation irrigation water management means controlling or regulating water application in a way that insures high crop yields without wasting water, soil, or plant nutrients. It means applying water according to crop needs in amounts that can be held in the soil available to crops and at rates consistent with the intake characteristics of the soil and the erosion hazard of the site.

An irrigator must have a reasonably good understanding of the basic principles of conservation irrigation. He must have a general idea of how water is held in the soil and released to plants and how much water his soils hold. He needs to know how to determine when to irrigate and how much water to apply. He needs to have a general understanding of soil-intake characteristics and of the adjustments in stream size and time of water application needed to fit the intake characteristics of his soils (chap. 1).

What the Planner Should Know

It is impossible to design an effective conservation irrigation system without complete understanding by both irrigator and planner. There should be mutual understanding of the water supply needed. The planner must know the farmer's wishes. He must consider the entire farm even if only one field is to be planned for irrigation at any one time.

Adequacy of Water Supply.--The first things to consider are availability, quality, and adequacy of the farm water supply. If there is no adequate supply or no possibility of developing one, further planning is a waste of time for both farmer and planner. Successful irrigation is not possible without a water supply adequate for the crops to be grown.

Farmer's Preferences.--Each farmer has a preference as to the kind of farm enterprise he wishes, which may dictate the kind of irrigation system and application method. He may have strong feelings about one application method over another. He may also be restricted by finances, availability of labor, and availability of construction materials and equipment. The designer should know how many hours per day the system is to be operated since this affects its design. No matter how technically sound a plan is, it cannot be effective if the farmer does not have confidence in the plan or the ability or desire to put it into operation.

Consider Entire Farm.--Seldom can all the irrigation facilities for an entire farm be established at one time. Usually specific fields or areas are planned individually, and establishment of an entire system takes several years. Fields or areas planned without considering the surrounding fields or areas may not fit in with future expansion. When these new areas are developed, it may be necessary to rework existing areas to make them a part of the overall system. This is costly and can be avoided if the planner studies the entire farm before planning any part of it.

Locate the high points in a field and determine the direction of irrigation and drainage. Determine the soil boundaries, probable crop rotations, and feasibility of land leveling. Locate field boundaries and farm roads. From this preliminary plan it should be possible to determine the best delivery point for the water.

Planning Procedure

After a preliminary plan has been made, studied, and discussed with the farmer, detailed plans for any area on the farm can then be prepared. First, select a method of water application for each field and prepare a layout. Then design the delivery, application, and disposal facilities as well as the necessary access roads.

Select Method

Determine the method or methods of water application best suited to each area or field. Several methods of application can be used on some sites and only one method on others. If more than one method can be used, study and evaluate each as to efficiency of water application and arrangement of irrigation units and other necessary facilities. In this way the method that best fits the fields and crops and is agreeable to the farmer can be used.

Layout

Planning a general layout for subdividing and irrigating the area in units of suitable dimensions is the next step. Areas delineated according to slope and soil characteristics provide a basis for selecting the best field arrangement and for locating field ditches.

Here again consider alternate layouts. Some layouts are more expensive than others and some are more suitable than others. Some desirable but

costly layouts may not be justified because of the farmer's financial resources or because of the low-value crops that are a part of the farm enterprise.

Application

Next design the application facilities. You can determine the amount of water that must be applied in a normal irrigation, the time allowed for applying it, and the rate at which it can be applied from the local irrigation guide. Then determine the amount of water that must be delivered to a field. Plan for land leveling if it is needed. Locate and design the head ditch or pipeline to fit the method of irrigation used. Locate and design ditches, pipes, levees, and the other structures needed to apply water to the field in the amount and rate required by the crop and soil.

Delivery

Plan the delivery facilities so that they permit delivery of water to the different fields in the volume and rate required by the method of application previously selected. Select and design the method of conveyance, either ditch or pipeline. Locate and design all the necessary grade-control and distribution-control structures, including measuring devices.

Disposal

Plan for the disposal of any irrigation waste water and excess rainfall promptly and safely. Consider recovery of waste water for reuse. Include all necessary disposal facilities--ditches, pipe, tile, structures, and pumps.

Factors in Planning

A well-designed conservation irrigation system delivers the required amount of water to all parts of the area to be irrigated at the required rate without damage to the soil or excessive loss of water. It is accessible and easy to operate without obstructing other farming operations. To plan such an irrigation system you must know the many factors that affect design in the area to be irrigated. Study such factors as soils, topography, crops to be irrigated, water supply, existing facilities, and available construction and farm equipment.

Soils

Soil is the foundation on which a conservation irrigation system must be built. It must be irrigable, that is, capable of sustaining yields high enough to pay the costs of development plus those of farming operations and maintenance. A farmer must be able to get a profit from irrigation without soil deterioration.

A soil survey is essential to irrigation planning. It is the basis for determining if the soils are irrigable and is used by the planner to fit the system to the soil. The location and extent of soils that differ

widely must be considered in deciding how an area can be subdivided, if necessary, so that suitable application methods and required amounts of water can be determined. The most important soil characteristic is its ability to take up and retain water. Other soil conditions that affect planning of irrigation should be noted, such as high water table, restrictions to drainage, erosion hazard, plowsoles and compacted areas, and high salt content.

To evaluate soil characteristics a knowledge of the physical properties of soil and how they affect the design and operation of irrigation systems is needed. Soil-plant-water relationships are discussed in chapter 1.

Intake Rates

You must know the rate at which water enters a soil under the varying land use and cropping conditions that may occur during the period when irrigation water is to be applied. Surface sealing, compaction, soil and water salts, sediment in irrigation water, soil erosion, land leveling, tillage practices, and other factors affect the intake rate of any soil. Any one or a combination may be present. These factors must be evaluated in determining the design intake rate.

The intake rate of a soil affects the method of water application, length of run, and time of application, which in turn affects the cost of a system. You must know the rate at which water passes through a soil to evaluate the possibilities for leaching and subsurface drainage. The ratio of lateral movement of moisture to downward movement is also important in selecting and designing some methods of water application.

Water-Holding Capacity

You must know the amount of water a soil can hold available to plants. The water-holding capacity limits the amount of water that can be applied at any one irrigation. For a given crop a soil with low water-holding capacity requires smaller and more frequent irrigations than a soil with high water-holding capacity. This is one factor in determining the number of days that can be allowed for applying irrigation water and hence is one basis for capacity and equipment design. The irrigation system must be designed so that water can be applied over the entire field before all the available stored moisture in any part of the field is used by a crop (chap. 1).

Depth

For irrigation soil depth is the depth from which a plant extracts moisture. A soil that permits normal root development and penetration provides maximum water storage. Restricting layers, such as rock, severely compacted layers, sand lenses, or a high water table, affect the moisture-storage capacity.

Other Characteristics

The depth to and thickness of layers having important textural or structural differences are important in design. Texture is closely associated

with workability and feasibility of using a soil for constructing earthworks such as ditches and dikes. Soil permeability is important in locating and building canals and reservoirs. Impermeable or very slowly permeable material affects construction costs and the type of construction used. Natural density of soil material and response to compaction is used in estimating the adjustments needed to balance cuts and fills for land leveling and in selecting material for the earth structures that may be required to support loads or restrain water movement.

It is highly important in land leveling to know the soil profile conditions and the maximum cut that can be made without seriously affecting agricultural production. If leveling will expose large areas of infertile subsoil, it may not be advisable to level the land for surface methods of water application and sprinklers may be needed instead. Exposing a small amount of infertile subsoil in a few small areas generally is permissible in leveling, especially if the improvement of an entire field depends on this exposure. The feasibility of restoring exposed subsoil to an economic level of productivity should be considered. Some subsoils respond quickly to needed soil-management treatments and others do not. But exposing a few nonproductive spots by grading usually is outweighed by the advantages of having a field properly leveled for efficient water application. If it is necessary to remove much topsoil in leveling, it may be advantageous to stockpile it and respread it on the exposed subsoil.

Drainage

Good drainage, both surface and internal, is essential to successful irrigation. If the land is not naturally well drained, artificial drainage must be established before or at the same time the irrigation system is installed. To plan a satisfactory irrigation system you must have a working knowledge of drainage.

In humid areas subsurface drainage is highly important if the soils are permeable enough for subsurface drains to be effective in lowering the water table to the depth required for good growing conditions. Surface drainage is always needed to remove excess runoff. Wet soils that delay planting in the spring, impede crop growth, and delay harvesting cannot be irrigated successfully.

In arid areas removing excess irrigation water, particularly ground water, is a primary function of drainage. Water lost through deep percolation increases the amount of ground water in a soil and may cause the water table to rise to a level at which crops are damaged. Subsurface drains are then necessary. Runoff from precipitation is usually small in arid and semiarid regions, and disposal ditches for any irrigation waste water are often adequate for disposing of any surface runoff from the low precipitation. Subsurface drainage may be needed to prevent or modify saline-alkali conditions in a soil by leaching.

Seepage from irrigation ditches can damage land and waste water. If site conditions require conveying water across gravelly, sandy, or other excessively permeable areas, the irrigation system design must provide for pipelines, flumes, or lined ditches as needed to prevent loss of water by seepage into the soil. Proper seepage control reduces the need for drainage. For additional information on drainage see section 16 of the National Engineering Handbook.

Erosion

Erosion, by either irrigation water or rain, can be a hazard to the operation and maintenance of an irrigation system. Furthermore, high yields of irrigated crops cannot be maintained on eroding land. Irrigation should not be planned for land subject to erosion until erosion control measures have been established or are provided for in the farm irrigation system. Erosion control practices and the irrigation system need to be fitted together for ease of operation and uniform distribution of water. Some soils are more susceptible to erosion than others. You must know the erodibility of the soils to be irrigated and then evaluate the factors that cause erosion and allow for them in planning the irrigation system.

Water erosion may be caused by the irrigation stream, runoff from adjacent areas, or water that falls directly on the irrigated area, either as rainfall or from sprinklers. You must provide for conveying and distributing irrigation water without damaging erosion. All unlined ditches must be located on nonerosive grades. If water must be carried down slopes steep enough to cause an excessive flow velociy, you must provide for erosion control structures, such as drops, chutes, buried pipelines, or erosion-resistant ditch linings in the design. Where flumes, chutes, or pipelines designed for high-velocity flows discharge into unlined ditches, you must plan stilling basins or other energy-dissipating devices.

The rate at which water is applied must be controlled so that it does not cause erosion. Some movement of soil particles always occurs when water flows over loose bare soil. If stream size is adjusted to the slope, erosion can be kept to a minimum for surface irrigation. In some areas it is rainfall amount and intensity and not irrigation stream size that governs the control measures used.

If sprinklers are to be used, you must design the rate of application so that it does not cause runoff that adds to the erosion hazard. This is particularly true in humid areas where a heavy rainstorm immediately after an irrigation may cause excessive runoff. Size of the drops from the sprinklers also is important. Large drops dislodge particles of soil that can easily be carried away by runoff water. On bare fields, new seedings, and row crops, rain or sprinkler irrigation may compact and seal the soil surface. This reduces water absorption and increases the erosion hazard. A crop cover or mulch dissipates the energy of falling water, and there is little or no surface sealing or erosion. In areas where the rate of precipitation is likely to exceed a soil's intake rate,

runoff and erosion may be a problem. This problem usually can be handled by installing conservation practices such as changing land cover, degree of slope, or length of slope. If runoff from adjacent areas is likely to cause erosion or flooding, plans must be made for either the diversion or controlled conveyance of the runoff water.

Winds damage crops, soil, topography, and irrigation structures and may affect the distribution of irrigation water. In areas where strong winds blow during the growing season, it is often necessary to establish remedial measures.

Winds may remove surface soil or deposit soil material on other areas. Soil removal can usually be reduced by vegetation, wind strips, tillage, or shelter belts. But these measures may lead to soil accumulation if adjacent areas are not similarly protected. Therefore, you must not only determine the probability of wind erosion on the area to be irrigated but also consider conditions on adjacent areas before selecting an irrigation method. Since canals, ditches, and other open structures may be rapidly filled by windborne materials, consider using closed conduits where this hazard exists.

Earth embankments, such as dams, canal banks, and border ridges or levees, may be damaged by wave action if long open reaches are parallel to the prevailing wind direction. This hazard can be overcome by locating these structures so as to reduce the fetch or by using riprap and other protective measures such as false berms or baffles.

Saline or Alkali Conditions

Saline or alkali soils require special irrigation planning. Selection of crops, fertilizer requirements, and the need for leaching and soil amendments must be considered. There may be some limitations on water-application methods that can be used.

Saline and alkali soils are generally restricted to arid regions where there is not enough rainfall to leach salt from the soil. But in areas where brackish water is used for irrigation, the soils may also show effects of salt accumulation.

Saline soils ordinarily are slightly alkaline in reaction (pH 7.0 to 8.5) but contain very little adsorbed sodium. They can often be recognized in the field by white salt crusts on the surface, by a damp oily-looking surface devoid of vegetation, by stunted crop plants that vary considerably in size and have deep blue-green foliage, and sometimes by tipburn and firing of leaf margins. To assess soil salinity, however, chemical and electrical-conductivity measurements must be made.

An alkali soil may be highly alkaline but not contain excessive amounts of soluble salts. These soils correspond to "black alkali" soils and often occur in small irregular areas called "slick spots." Sodium usually is the dominant cation in alkali soils.

A saline-alkali soil contains excessive amounts of both soluble salts and adsorbed sodium. As long as they contain excess salts, these soils usually are similar in appearance and properties to saline soils. If the excess soluble salts are leached out, the soil properties may change markedly and become similar to those of alkali soils. They become strongly alkaline, soil particles disperse, and the soils become unfavorable for the entry and movement of water and gases and for tillage.

A high salt concentration in the soil solution interferes with the ability of a plant to absorb both moisture and plant nutrients from the soil. If too high in the root zone, it is detrimental to plant growth regardless of the kind of salt present. Small quantities of some salts may reduce yields of sensitive crops and only slightly larger amounts may prevent crop growth. Some alkali salts cause undesirable changes in the physical condition of soils, reducing permeability and increasing the difficulty of cultivation.

Saline soils can be improved by leaching--applying extra water to a field and allowing it to soak through the soil, draining the salts away. Alkali soils can be improved by adding chemicals such as gypsum or sulfur, leaching the soil, and then using practices that build soil structure. Saline-alkali soils can be improved in the same way. Usually it is best to apply the chemicals before leaching.

Topography

Topography is a major factor in determining the feasibility of irrigation, selecting the method of irrigation, estimating the number and kind of water-control structures needed, and determining the need for land leveling. The relative elevation of the water source, the land surface between the water source and the area to be irrigated, the different parts of the area to be irrigated, and the drainage outlets are the important topographic features that must be known to properly plan a farm conservation irrigation system. You may be able to learn enough by a simple inspection, or you may need to make a survey. Detailed surveys are generally needed to design a system.

The kind of topographic survey needed depends on the irrigation method to be used and irregularity of the ground surface. Since detailed topographic surveys are time consuming and expensive, get only enough information to permit sound and accurate planning. Any topographic survey begins with a base map that shows boundaries and dimensions of the fields to be irrigated and location of the water supply. Such a map can be made by tracing an enlarged aerial photo, usually at a scale of 50 to 200 feet to the inch.

The general topographic information needed for planning most irrigation systems and methods of application includes as a minimum the following:

1. Source and elevation of the water supply for the area under consideration

2. Landscape features, such as fences, buildings, roads, and shelterbelts, that influence the layout and design of the system
3. Present field boundaries
4. Drainage pattern of the farm, including outlets

Additional topographic information needed depends on the method of water application.

Sprinkler Irrigation

For planning sprinkler irrigation systems, the following additional topographic information is generally needed:

1. Direction of land slope to locate laterals and main lines
2. Changes in elevation along lateral-line settings to design a system that controls variations in sprinkler discharge
3. Maximum differences in elevation along the main line and between the irrigated area and the water source

If slopes are gentle and fairly uniform, checking the elevation at a few points along the side of the field, at control points along possible main-line locations, and at the water source is enough. On rolling land or if crop rows must be on the contour, or on level land where surface drainage is a problem, a more detailed survey is needed, including a contour map of the area to be irrigated.

Surface Irrigation

For surface methods not requiring land leveling, a less detailed survey will suffice. Generally about all that is needed is the elevation of natural ridges, depressions, and other features that influence location of contour ditches, field supply ditches, and drainage ditches.

If water is to be applied by graded borders, furrows, or other surface methods requiring land leveling, a complete topographic survey is required. It must show the slope and surface features needing correction by land leveling as well as the direction of irrigation.

Subirrigation

If a field is to be subirrigated, you must know the general topography to locate water-application conduits and water-level-control structures. The intensity of survey needed varies with location. For nearly level uniform fields you need only those elevations that show the general slope, ridges, and depressions. For other fields a topographic map may be needed, particularly if land leveling is needed to keep the water table at the same depth between distribution ditches or tile lines.

Supply Lines

If open ditches or permanent buried pipelines are to carry water from the source to the field supply ditches, determine their location by standard route-type survey. You need a profile of each proposed centerline and, to compute the amount of excavation needed, a cross section also.

Conservation Practices

If terraces are to be used with sprinklers or contour furrows, you need enough topographic information to lay out the terraces and to locate and plan the terrace outlets. If contour bench leveling is proposed for reducing grade on a field where steep slopes make surface irrigation difficult and hazardous, you need detailed topographic information (chap. 12, Land Leveling).

Water Supply

A supply of water adequate for the needs of the crops to be irrigated must be available when needed. Water supply is often the controlling factor in irrigation feasibility and the number of acres that can be irrigated. Make a detailed inventory before planning to make sure that the available water supply is adequate. Find out the possible sources and the rate, quality, and quantity of water available at each location. Determine seasonal variations in supply as well as those during the growing season. You may need to study the supply by months or shorter periods in relation to crop requirements. The irrigator's water rights should also be known.

Water Rights

Water rights are the legal means by which water can be used. In areas covered by legislative codes, the procedures for acquiring water rights have been devised primarily to protect their owners. In areas not covered by legislative codes, it is advisable for a water user to establish the initial date and amount of appropriation, the point of diversion, and the period of use by witness affidavit in a form acceptable to a court or jurisdiction in the event of water legislation or suits contesting water rights.

The eastern part of the United States is not covered by legislative codes, but water use is based upon the riparian principle. Under this principle, owners of land touching a stream have equal rights to use of the water. Other landowners do not have such rights. The riparian owner has the right to have a stream flow past his land substantially unimpaired in quality and undiminished in quantity by water users above him. Each riparian landowner, however, may make reasonable use of the water for domestic or other purposes. All domestic uses must be satisfied before any water can be taken for nondomestic uses. What is reasonable use depends on supply, kind and means of use, and other circumstances at the particular time and place. Because riparian rights are not well defined, investments in water development based on riparian rights are not as dependable as they should be. Ground-water rights are based on both court decisions and legislative acts. Ground-water rights vary by State and often do not offer much protection.

All the 17 Western States have prior-appropriation laws. Under this principle the first or earlier user of water for a beneficial purpose has the best right. His right is specific as to time, place, and amount. The right of others to use water from a source is subject to the right

of the prior user. In times of shortage any reduction to users is in the reverse order by which water rights were obtained. Therefore in the West, if an irrigator has a water right, it is usually good to the extent of his priority and most water rights are well defined.

Procuring or establishing water rights is a responsibility of the water user.

Quantity

The quantity of irrigation water required for any particular period should equal or exceed the gross irrigation requirement for that period. To this amount must be added any water required for leaching, temperature control, or frost control.

In addition to the total amount of water required, rate of delivery is an important factor in designing and operating an irrigation system. Soil moisture must be replaced before crop production is reduced by the lack of available moisture in the soil. The rate of delivery per unit of area must be equal to the gross application per irrigation for the specified operating time.

Rate of delivery can be computed by the equation

$$Q = \frac{453Ad}{FH}$$

where Q = rate of delivery in gallons per minute

A = acreage of design area

d = gross depth of application in acre-inches per acre

F = number of days allowed for completion of one irrigation

H = number of actual operating hours per day

Factors (d) and (F) can be obtained from the local irrigation guide. Factors (A) and (d) are set, but F and H can be varied according to a farmer's wishes. The guide gives the maximum number of days that can be allowed for completing one irrigation (F). The number of actual operating hours per day (H) must be the farmer's decision. He may wish to irrigate his acreage in less than the allowable number of days or he may have labor available for only part of a day.

Delivery may be continuous, on demand or modified demand, or at fixed intervals (rotation). Demand or modified demand schedules of delivery are preferred. Continuous and fixed schedules of delivery do not give enough consideration to variations in rainfall and consumptive use. But for some crops and irrigation systems demand delivery may be the same as continuous for most of the irrigation season.

In determining the net irrigation requirement, calculate consumptive use for the crops to be grown. The net irrigation water requirement for a crop is total consumptive use of the crop less effective growing-season rainfall, carry-over soil moisture from winter rains, and any moisture from ground water. By applying the expected field application efficiency to the net irrigation water requirement you arrive at the gross field requirement. To this figure add expected water losses from the source to the point of application and any amount needed for leaching, temperature control, etc., to get the total quantity of irrigation water needed. Consumptive use, effective rainfall, carry-over soil moisture, and irrigation efficiency are discussed in detail in other chapters of section 15 of the National Engineering Handbook.

Getting a dependable water supply cannot be based on the average requirement since the supply would be adequate approximately half the time. It is common practice, therefore, to estimate water needs on a probability basis. High-value crops may justify a water supply that is adequate 9 years in 10. On the other hand for a low-value crop, such as hay or pasture, it may not be economical to provide an adequate supply more than 5 years in 10. Each case must be analyzed individually.

Quality

Quality is important in evaluating irrigation water supply. Unless water quality has been determined previously, have an analysis made and evaluated before recommending the water for irrigation. Generally impurities carried in solution determine water quality. But those in suspension may have important effects on quality. Whether water of a certain quality is suitable depends on local conditions--climate, soils, crops grown, and depth of water applied.

Rainfall and snowmelt pick up soluble salts and silt particles as they flow along the ground surface to streams. Water flowing in stream channels picks up additional impurities. Runoff water and excess irrigation water that infiltrate into a soil pick up soluble compounds as they percolate through earth formations to streams or to underground reservoirs. Percolating water commonly dissolves more salts than surface water. Unless surface water flows over exposed beds of soluble material, it seldom has a high salt concentration. But stream flows during low-water periods, when discharge is maintained by ground-water runoff, contain higher concentrations of salts than stream flows during high-water periods. Salt concentration in streams flowing through irrigated regions often increases during summer and fall as water moves downstream because of heavily charged return flows of excess irrigation water. In general the proportion of salts in irrigation water is greater (1) in ground-water runoff than in surface runoff, (2) during low stream flow than during high-stream flow, (3) downstream than upstream, and (4) in underground reservoirs than in surface reservoirs.

Stream pollution from industrial wastes and tide and wind conditions affect the quality of irrigation water. Special studies and additional water-analysis data are necessary to evaluate quality fully.

Brackish water is contaminated by acids, basic salts, or organic matter, whereas saline water contains only dissolved salts. Sea water is the chief contaminant of brackish water. Salts may accumulate in soils in humid areas if brackish water is used for irrigation. But because of rainfall and the usually light applications of irrigation water, salt accumulation is usually confined to the upper foot of soil. In areas of high rainfall, winter rains usually leach salts out of the root zone if internal drainage is good.

The amount of brackish water that can be used depends on its salt concentration, number of irrigations between leaching rains, salt tolerance of the crop, and salt content of the soil before irrigation. You should determine the salt content of the irrigation water, check the accumulation of salt in the soil, and know the salt-tolerant crops that can be grown on the area to be irrigated.

Type of Supply

The basic source of water for irrigation is precipitation. Sources of supply are usually considered in two general classes, surface and subsurface. A third miscellaneous class includes city water, sewage, and industrial wastes. The type of supply, particularly its rate of delivery, has some bearing on method of water application and layout of an irrigation system. Various types of water supply are discussed in the following paragraphs. In general water for irrigation is obtained from one primary source, but in some places an additional supply is required from a supplemental source.

Surface Water.--Surface water is a principal source of water for irrigation. Surface supplies include water diverted or pumped from streams; water released from lakes or reservoirs directly into a farm irrigation system or into canals leading to a farm; water pumped from lakes, reservoirs, and canals, or obtained from other surface sources. Excess irrigation water that reaches streams through surface drainage, flow through drainage ditches, or percolating return flow from irrigated land and available for rediversion is generally considered a surface supply.

Streams.--Streamflow is generally the cheapest source of water for irrigation. It is also the least dependable supply. In the East where water rights follow the riparian doctrine, its use is limited to farms abutting the streams. Year-round streams, usually rivers and large creeks, generally are a good source of water. Smaller streams that are dependent almost entirely on rainfall have their lowest flow during the long dry periods when water needs are greatest.

A perennial stream is a dependable source only as long as the acreage to be irrigated needs no more water than the stream produces during drought periods. If the acreage to be irrigated requires more water than the dry-weather flow, the water must be impounded to insure an adequate source. Smaller perennial streams and intermittent streams are not dependable sources unless their water can be impounded.

Unless a stream is large enough that its adequacy as a supply is obvious, it is necessary to determine the dependable dry-weather flow. The U.S. Geological Survey or some other Federal or State agency may have gaged the stream and can furnish data for determining its dependability. If not, it is necessary to measure the flow during a prolonged dry period.

Storage Supplies.--Storage supplies include water held in natural lakes and surface reservoirs. Reservoirs storing water for irrigation range from small impounding or excavated farm ponds to large impounding mainstream reservoirs. Usually large reservoirs are built to furnish water to a group or groups of farmers through some kind of legal organization, such as an irrigation district or conservancy district. Small farm ponds usually are built for use on single farms.

The watershed yield for an impounding irrigation reservoir must be enough to provide the necessary supply during years of low yield. A study of rainfall and runoff records or stream gaging may be necessary to determine this yield. In addition to capacity for storing the gross irrigation-water requirements, allowance must be made for loss of water by evaporation and seepage and capacity loss through siltation (fig. 3-2).

Depth of the water that may be lost through evaporation can be estimated by procedures given in section 4 of the National Engineering Handbook.

Seepage depends on permeability of soil and rock materials at the reservoir site, elevation of the water table in the surrounding formation, hydrostatic head produced by stored water, embankment material, and construction methods. No large reservoir should be constructed without thorough geologic investigation and approval of a competent engineering geologist.

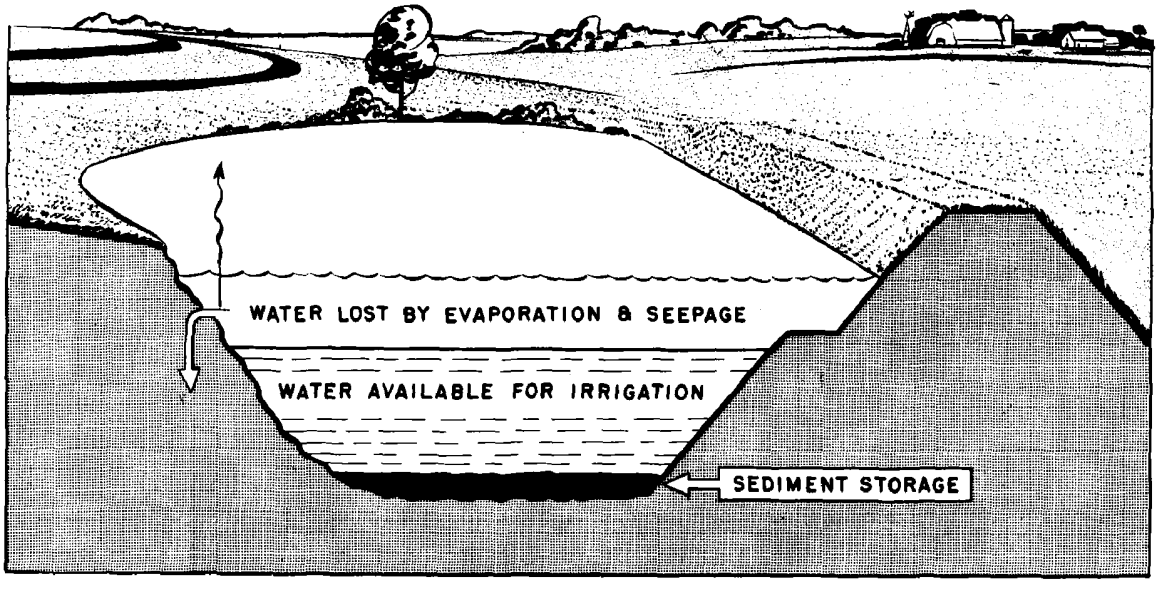


Figure 3-2.--Water loss in an irrigation reservoir.

The capacity required for sediment storage depends on geologic, topographic, and hydrologic conditions throughout the drainage area above a reservoir site. Conservation practices should be established on the watershed before the reservoir is built to hold sediment production to a minimum. Loss of capacity by siltation in small farm reservoirs can often be estimated by studying the effect on similar reservoirs in the immediate area having like topographic and soil conditions. For larger reservoirs or where there are no comparable reservoirs, a detailed study must be made of the likely sediment problem.

Natural lakes are a good source of irrigation water, but often withdrawal of water for irrigation is restricted. More and more of our natural lakes are being developed for recreation and residential use, and everything possible is being done to maintain lake levels. Unless a lake is large or a farmer's land completely surrounds it, or he has legal right to use the water, he may not have a dependable source of irrigation water.

Offstream storage should be considered if streamflow is not enough to provide the required amount of irrigation water or if damming a stream is not possible or feasible. Floodflow in the stream can be diverted through a pipe or open ditch or pumped into an offstream reservoir. The water thus stored can then be used during the low dry-weather streamflow. This method also has the advantage of not interfering with low streamflow, which is important in areas governed by riparian rights. If floodflow is to be impounded, it is necessary to study the floodflow characteristics of a stream to determine if floodflow provides enough water in years of low rainfall or snowmelt. Reservoir capacity should be enough to supply irrigation needs when streamflow is too low to meet them.

At some sites it may be possible to construct an earthen embankment across a gully or small valley that contributes to the stream if the watershed above the embankment is not large enough to furnish the necessary irrigation water. Some runoff can be stored and it is necessary only to pump enough water to fill the reservoir before the irrigation season begins (fig. 3-3).

Supply Canals.--Canals are used to furnish water to groups of irrigators. Water for the canal can come from a reservoir, stream diversion, pumping, or some other source. The supply is controlled by the group or irrigation district. The time and amount of delivery can be continuous, on demand, or at scheduled intervals. Location of the canal with respect to the area to be irrigated and time of delivery of the irrigation water has considerable effect on layout, design, and operation of a farm irrigation system.

Return Flow.--Return flow from an irrigated area is part of the diverted water that finds its way back to a stream channel. It includes surface runoff during irrigation, drainage from canal seepage, leakage at canal structures, waste-water discharge during conveyance, discharge at the

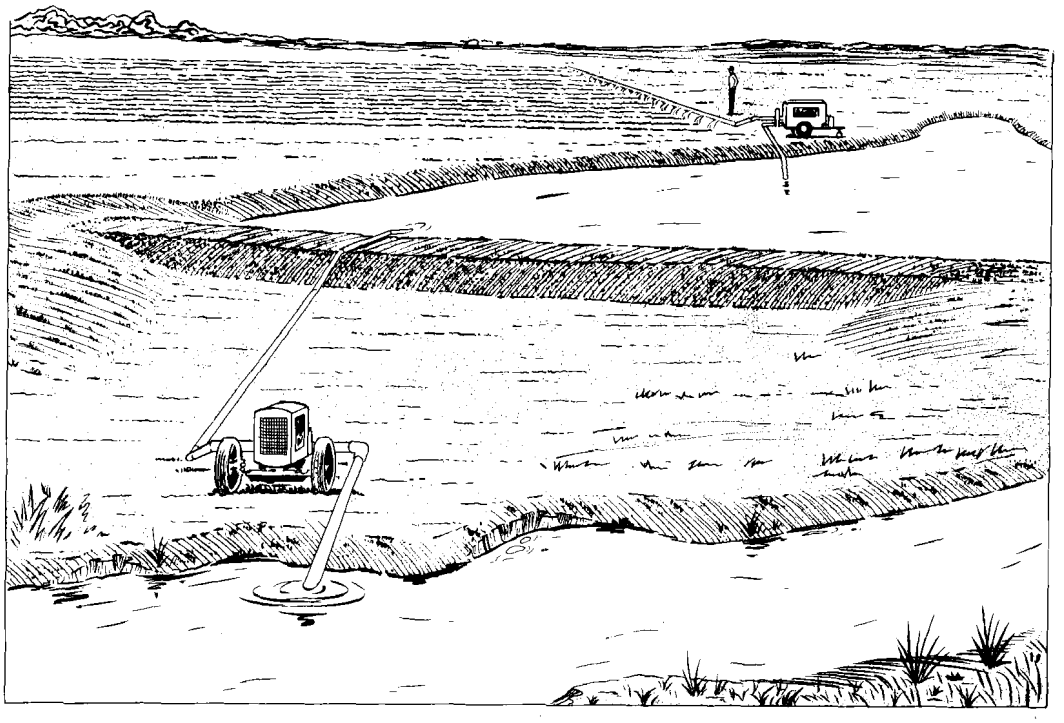


Figure 3-3.--Off-stream storage reservoir.

lower end of the canal, and drainage from excess percolation during irrigation. Return flow can be used to irrigate land below the serviced area or it can be captured for use as supplemental water. The amount of return flow depends on the amount and timing of water diverted, conveyance and irrigation efficiency, subsurface soil formations, surface soil texture, and drainage facilities. It is sometimes possible to impound out-of-season return flow in reservoirs for use during the next irrigation season.

Tail-Water Recovery.--To obtain high efficiency in graded-border or furrow irrigation, it may be necessary to permit some surface runoff at the lower end of a field. In some areas of shallow soils or steep grades, it may not be practical to level land properly. If the water supply is limited, it is often economically feasible to recover this waste water or tail water and pump it back into the delivery system or storage reservoir for reuse, either on the same field or adjacent fields.

The structures required usually consist of a pickup ditch that directs water to a sump or storage basin and a pump and pipelines to deliver water to the desired elevation for reuse. Pickup ditches should be large enough for both irrigation water and runoff from rainfall. Sumps and pumps should have adequate capacity to insure efficient use of the pump-back stream in the irrigation system. If the capacity of the sump or storage pit is low in relation to the volume of runoff that can be expected, automatic controls on the pump are recommended.

Tail-water recovery facilities should not be installed as a substitute for good irrigation water management but as a supplement to increase irrigation efficiency. For furrow irrigation, a tail-water recovery system also can be used to eliminate the labor required for cutback streams while maintaining high efficiency.

Drainage Recovery.--The amount of water that can be recovered by draining an irrigated area depends on soils, losses and waste during conveyance, and excess water delivered to irrigated fields. It is not economical to drain irrigated land for the sole purpose of recovering water. The main purpose of drainage is to reclaim seep areas and prevent further damage to the land. The water recovered may be of lower quality and is generally a supplemental supply that can be used on lower lying land. In some places adequate drainage can be obtained by pumping deep wells near irrigation canals and laterals. The water can be pumped into a canal or lateral to provide an additional supply. For this method to be feasible the underground formation must be porous, extend to considerable depths, and be continuous through a large area so that the water can be drawn from a long distance.

Subsurface Supplies.--Subsurface water is obtained by pumping porous or cavernous formations, using flowing artesian wells, or collecting the flow from large natural springs or seepage areas. Ground water has the advantage of being free from weed seeds and debris, which is particularly important in sprinkler irrigation. Subsurface water supplies are usually developed and operated by individual farmers or by a few landowners working together. The best source of information about availability of ground water is usually a State geologist or a Federal ground-water survey. Local well drillers can also give helpful information.

Wells.--Most irrigation water from subsurface sources comes from wells. An irrigation well consists of a hole, with or without a supporting casing, extending from the ground surface to or into a water-bearing formation. If the well is properly constructed and developed, the maximum amount of water that the water-bearing formation can supply can be pumped. In areas where ground water is plentiful, wells can usually be located near the center of the irrigated area for convenience and economy of pumping.

The requirements for an irrigation well are:

1. The lift should be as small as possible.
2. The well should have a long life.
3. The water pumped must be reasonably free of sand.

Three general kinds of water-bearing formations require pumping plants--sandstone formations, gyp or limestone caverns, and unconsolidated sand and gravel formations.

For sandstone formations, wells are drilled through the water-bearing sandstone, but the casing is set only from the ground surface to the upper limits of the sandstone except in formations that tend to cave. For those wells, the casing extends through the unstable formation.

In limestone and gypsum formations that contain numerous holes or caverns, wells are drilled from the surface through the limestone or gypsum into the cavern, and the casing is set from the surface down to and bedded in the rock.

In unconsolidated sands or gravels, wells are drilled through the water-bearing formation, and the casing is set the entire depth of the well. The lower end of the casing consists of either a perforated section or a well screen that permits water to pass from the water-bearing sands or gravels into the well.

A group of wells drilled in one of these formations has certain general group characteristics, but each well must be individually analyzed, designed, and constructed. No two water-bearing formations are exactly alike, and no well should be drilled and developed exactly like a nearby well without first determining the best development procedures.

Wells are dug, driven, or drilled depending on the depth to which they must go, nature of the materials through which they must pass, rate at which water is to be removed, and elevation of the ground-water table.

Dug or open-pit wells are usually excavated by hand into the water-bearing strata. Before modern well-drilling equipment was available, most wells were dug. They are most practical for (1) developing shallow thin water-bearing strata that require large-diameter wells and (2) installing a pumping unit close to the ground-water table.

Driven wells are constructed by forcing a pipe into the ground until it penetrates the water-bearing strata. They are limited to depths of less than 50 feet in soft material.

If the water-bearing materials are near the surface but are not deep enough to supply enough water through a single well, a battery of sand-point wells can be connected to a pumping unit by a manifold. In planning a well-point system it is important to space individual wells so that their areas of influence overlap only slightly or not at all. Although it is seldom practical to calculate the size and shape of the areas of influence because of the cost of making the tests needed to measure the drawdown curve, some general rules based on judgment and experience can be followed in spacing the wells.

A spacing of 25 to 50 feet between sand points generally has worked nicely. Wells can be closer together in fine sand formations and where the aquifer is thin. They can be farther apart if the aquifer is deep enough and thick enough to permit installing long well screens (10 feet or more) in the wells.

Drilled wells are put down by percussion drills or rotary drills or some modification of these tools. They can be drilled to any desired diameter to about 36 inches, through almost any material, and to any practical depth. For these reasons drilled wells are the most common irrigation wells. A casing is installed in the drilled hole down to the water-bearing strata and a well screen is attached to the bottom of the casing. If the aquifer is predominantly sand, a perforated casing with a graded gravel pack is generally used instead of a well screen.

Artesian Water Supplies.--Water from flowing artesian wells or pumped from artesian aquifers can be used for irrigation. Substantial amounts of water can be obtained from artesian aquifers that underlie large areas and carry water under relatively high pressure. Annual withdrawal should not exceed annual recharge continuously. Otherwise artesian pressure decreases, flowing wells soon cease to discharge, and pumping is necessary. Eventually the supply of water is not adequate for proper irrigation.

Springs.--Natural springs near the land to be irrigated can be used as a water source for irrigation water if they discharge appreciable flows during the irrigation season. Usually the discharge is not enough to provide an adequate irrigation stream, and some kind of storage basin is required. If there is a series of springs in a given area, it may be possible to collect the discharge into one channel. A perched or contact spring is usually the least dependable because of the limited flow available. An artesian spring usually is the most dependable. Dependability of springs is difficult to estimate because of the many variables that affect the source of supply. The kind of spring, conditions found during exploratory excavation, and local information on past behavior of the spring are all factors that must be considered. The capacity of springs can often be improved by excavating, cleaning, capping, or providing collection and storage facilities. Sound judgment must be used to avoid expensive development of springs that may soon go dry.

Seepage.--Underground seepage water can be intercepted and stored in excavated reservoirs in some localities and used for irrigating small areas (fig. 3-4). Reservoirs usually are excavated in low-lying level areas where lateral movement of water underground replenishes the supply. Dependability as a source requires a high natural water table under adjacent land and a highly permeable layer that permits rapid lateral movement of water within a practical excavating depth, usually 12 to 20 feet. The success of these reservoirs depends on the rate of recharge because most of them are small. The most successful reservoir is one large enough to provide a full day's irrigation from storage and inflow and is refilled by seepage during the night. In some places additional water can be captured from springs, tile lines, or surface runoff.

Regulating Storage Reservoirs.--If economically attainable flow is too small for irrigating directly from a well or spring, regulating reservoirs can be used to advantage (fig. 3-5). Continuous small flow can be stored in a regulating reservoir, thus providing enough flow at a rate

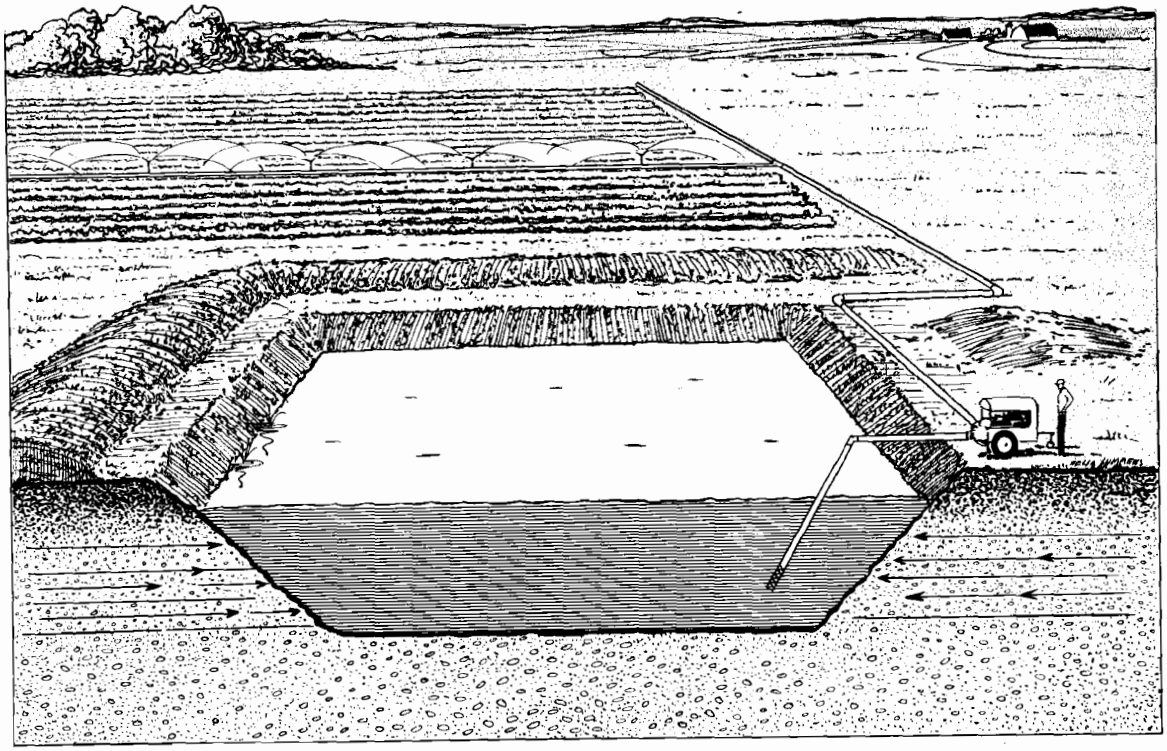


Figure 3-4.--Ground-water storage reservoir.

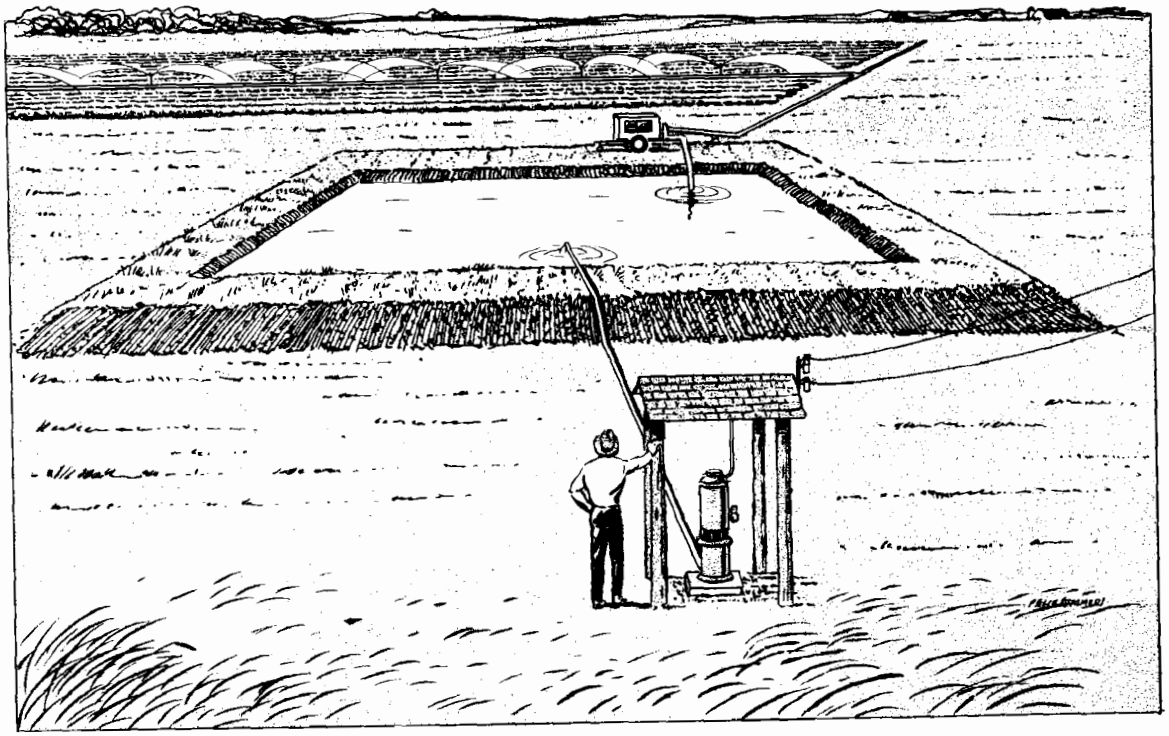


Figure 3-5.--Regulating reservoir.

to operate the required size of irrigation system to make an irrigation application. In other words, flow into the reservoir is continuous but the irrigation equipment is operated intermittently. The timing depends on size of the irrigation system, storage capacity of the reservoir, and inflow rate.

Regulating reservoirs are built either by excavating a pit and using the spoil material to build a levee around it or by building an earthen dam across a low area. Size is generally determined by the amount of water needed for one day's operation. The reservoir should be large enough to store all inflow while the irrigation system is not in operation. For example, if the source of water is a small well pumping 24 hours a day at 200 gallons per minute and the irrigation system uses 400 gallons per minute, the system can be operated 12 hours a day if the reservoir is large enough to store water for 12 hours of pumping. The rate of discharge should be determined for the period of lowest flow so that enough water can be stored for low-flow periods. A regulating reservoir can also be used to store continuous small deliveries from canals and laterals. Often it is called an overnight-storage reservoir.

Miscellaneous Sources.--Minor sources of water are city water, effluent from sewage-treatment plants, and waste water from industrial plants. The quantity of water available from these sources is usually small and only enough for irrigating small areas near the point of disposal.

City Water.--City water can be used for irrigating suburban land. Water from city mains, although usually too expensive and inaccessible for general farm use, has been used on some small areas of high-value crops near towns. Although water costs are high compared to those for other supplies, for small systems water pressure in the city mains is enough for irrigating small areas without using booster pumps, thus avoiding pumping costs. Size of the main and water pressure affects rate of delivery and consequently design of the irrigation system.

Sewage Water.--Effluent from sewage-treatment plants can be used for irrigating nearby small areas. Sewage discharge is return flow from domestic and industrial uses. Since it often amounts to two-thirds or more of the water delivered to consumers, sewage flow from large cities can be an important source of water for irrigation.

In considering the use of sewage effluent for irrigation, the possibility of contaminating crops and polluting ground water must be investigated. Many States have regulations governing the use of sewage effluent for irrigation. Check the State regulations before doing any irrigation planning that considers using sewage effluent as the water supply. Sewage effluent is more suitable for use on coarse-textured sandy soils than on fine-textured silt and clay soils. The fine sediments in sewage flows may improve the structure of sandy soils. Deposition of these sediments on the soil surface can decrease the permeability of silt and clay soils.

Industrial Waste Water.--Waste water from food processing and canning plants can be used for irrigation if there is a supplemental supply that can be used during the part of the season the plant is not in operation. Continuous flow from other kinds of industrial plants may be a good source of water if it does not contain harmful chemicals and sediments. In any case the water should be analyzed to determine if its use will have harmful effects on the crop or soils. Most of this waste water carries sediments in suspension that may affect the type and design of an irrigation system.

Location of Supply

Location of the water supply has considerable effect on the layout, design, and operation of an irrigation system. In many places location is fixed by conditions beyond your control as a planner. You must then fit the irrigation system as best you can to the fixed location. If there is a choice, locate the supply at the point that will give the lowest estimated cost of delivery to each part of the irrigation system. Consider the following general points.

1. Accessibility for operation and service
2. Length of delivery facilities to each field in the system
3. Erosion protection for supply ditches
4. Possible use of gravity flow from the point of supply
5. Location of temporary storage reservoirs if needed

The location of natural lakes is fixed and there is generally little opportunity for choice in the location of impounding or excavated reserviors. If the water supply is to be pumped for surface irrigation, it is usually located at the highest point in the field or near the highest point, which may or may not be the best location. Often it is desirable to locate the supply somewhat below the highest point of the field and to carry the required amount of water necessary to irrigate the higher area to the top of the slope in a pipeline. This is the best plan if the high area is a knoll constituting only a small part of the field and the remainder of the irrigated area is several feet lower. If the source is a well at the high point of the field, all the water for irrigating the entire field must be pumped to this elevation. It is then carried back down the slope to the point of use in a pipe or through a series of ditch checks that control velocity. Since pumping cost is directly proportional to pumping lift, it increases in proportion to any added lift. If the source is a group or district canal, its location is generally fixed at or near the high point of the area to be irrigated and there is little choice in location of the point of takeout.

Wells generally offer the most flexibility in location. In some places location is fixed because of availability of an adequate aquifer. If the

aquifer is extensive, the well generally can be located at the most advantageous point.

If a sprinkler system is planned, usually the well should be near the center of the land to be irrigated. The saving obtained through proper location can amount to several hundred dollars through the smaller pipe and shorter main line that can be used. For surface irrigation using either surface or underground pipe, the well should be located where the shortest and smallest (diameter) pipeline can be used to service the area to be irrigated. This location depends on topography of the field and design of the water-application system.

Wells are often located close to a farmstead merely for convenience in servicing. In addition to any extra pumping costs caused by this location and the cost of extra pipe and ditches, the well often interferes with or may even dry up domestic wells on the farmstead. Convenience in servicing well pumps and motors is important in chosing the location. Access lanes from the farmstead to the well should always be provided.

Generally, there is little choice in location of the takeout if irrigating from natural streams. If the stream flows through the area to be irrigated, it may be possible to adjust the point of takeout to fit in with the overall layout of the farm irrigation system. It may be advantageous to consider more than one takeout from the stream. Topography and stream location are the major factors to consider in selecting the point of takeout.

Climate

Climate is a factor affecting irrigation for an entire area. For irrigation its classification--humid, semiarid, and arid--generally is based on precipitation. Humid regions receive more than 30 inches of precipitation, semiarid 15 to 30 inches, and arid less than 15 inches. Climate directly affects the growth habits and requirements of plants (chap. 1). Therefore a conservation irrigation system must be designed so that it works in the existing climatic conditions.

Precipitation

Annual precipitation determines the amount of water available for irrigation storage. Rainfall during the growing season, particularly its distribution, affects the amount and frequency of irrigation needed. Land receiving an appreciable amount of rainfall during the growing season may need only a small amount of irrigation water, depending upon rainfall distribution. In some years of adequate rainfall well distributed, irrigation may not be needed at all. Land that receives enough rain in the spring to fill the root zone may not require irrigation until the crops have attained considerable growth. Land that receives only small amounts of rain during the spring and summer months requires the most irrigation water, and the irrigation system must be designed to supply the full amount of water needed for good crop production.

Excessive precipitation or high-intensity rainfall produces runoff that may result in erosion and make drainage necessary. Irrigation planning must take into consideration drainage and erosion control measures.

Temperature

Temperature directly affects water requirements for crop production and the design of an irrigation system. Growth of most plants is slowed or arrested at low temperatures. Since evaporation and transpiration are rapid at high temperatures, soil moisture is soon depleted.

Length of the growing season and temperatures during the growing season determine the kinds of crops that can be grown profitably. It is possible to lengthen the growing season for some crops by irrigating. Strawberries have been protected successfully against late-spring frosts. Cranberries and low-growing vegetable crops, such as tomatoes, cucumbers, peppers, beans, and squash, have been provided time to mature near the end of the season by irrigating. Chapter 11 of section 15 outlines design information on sprinkler irrigation for frost protection.

Irrigation can be used to control high daytime temperatures that otherwise reduce the quantity and quality of fruit. Sprinkler irrigation during the heat of the day can reduce field temperatures around a plant as much as 15° to 20° F. and increase humidity by 15 to 25 percent. The sprinklers must be designed to apply as near a fine mist as possible over the entire field (as in a frost-control system). They are turned on when high temperatures that seriously affect a plant are reached and are operated until the temperature has dropped below the danger stage.

Inclusion of frost protection or temperature control in an irrigation system affects the selection of application method as well as the planning, design, layout, and operation of the system.

Farm Enterprise

Before planning a farm irrigation system, you must know the type of farm enterprise--livestock, cash crops, or a combination--as well as the farm operation schedule planned and the labor available for irrigating. All these factors influence the choice of water-application method, layout and operation of the irrigation system, and intensity of irrigation. The kind of crops to be grown and available labor are the most important items to consider.

Crops

Some crops need more water for high yields than others. Some use more water (peak use) during the early part of the growing season and others, later in the season. Crops that mature during the early part of the growing season generally have a lower peak-period use rate than those maturing in the latter part. The moisture-extraction pattern of shallow-rooted and deep-rooted crops varies considerably, which affects the amount of water to be applied at each irrigation and frequency of irrigation (chap. 1).

Know the acreage and field boundaries for each kind of crop and the rotation planned. Consider the cover and soil-improving crops to be grown in the rotation as well as the row crops. Any irrigation system designed for a field must meet the requirements for conservation irrigation of all the crops to be grown. The kind of crop to be grown usually determines the choice of water-application method.

Labor

Irrigation usually requires extra farm labor. The amount depends on the type of system, water-application method, and labor-saving devices installed with the system. Even for nearly automatic systems, it is necessary to have someone watch the operation closely if high efficiency is to be attained. Get a clear picture of farm schedules to know how much time can be devoted each day to irrigation without neglecting other work. From this information you will know if full-time irrigators are needed during the growing season or if regular farm labor can be used at different times of the day or night. Plan the irrigation system with the farmer's labor supply in mind. If he has plenty of labor, it is generally possible to provide a system of lower initial cost because labor-saving devices are not needed. If he does not have much help, various degrees of automation can be built into the system but this increases the initial cost over that for a hand-operated system.

Field Arrangement

Having fields of workable size and shape is important to successful irrigation farming. Often both size and shape must be changed to provide an efficient irrigation system. Unless a system is carefully planned, some areas may not receive irrigation water or some small areas may be virtually inaccessible or useless to the farm enterprise. Sharp turns or acute farming angles difficult or impossible to farm with modern farm equipment must be avoided. To have fields that can be farmed economically and irrigated with one or more uniform sets, use the following criteria for size and shape.

1. Base length on the maximum allowable run for the method selected. It can be in even multiples of the proper design length.
2. Base width on the cropping system, operations schedule, and type of equipment.
3. Base field divisions on ownership boundaries, obstructions, soil boundaries, land slopes, and land use or cropping system.
4. Plan fields as nearly rectangular in shape as possible.
   a. Plan length of run to be uniform to permit a workable operating schedule.
   b. Avoid sharp turns or block corners.
5. Remember the importance of good accessibility.

Farm Equipment Available

A farmer's present equipment for planting, tillage, and harvesting may have some bearing on selection of irrigation method and layout of the

system. It may be better and more economical for some irrigators to get different farm equipment to have a better and more efficient irrigation system. The question of farm equipment should be settled before the final planning so that the system installed is compatible with the farm equipment to be used.

Available Power

Determine and compare the sources of power available for operating the irrigation system. If electricity, note the location of the nearest transformer and other features, such as phase, voltage, and horsepower limitations. Pay particular attention to power rates and standby charges.

Existing Facilities

It is particularly important in planning the rehabilitation of an irrigation system to find ways of using the present facilities before considering any changes in method or system layout that necessitate abandoning or relocating permanent structures. If possible, make some use of any equipment already on a farm if it is in good condition. But under no circumstances should you plan for a less efficient irrigation method not suited to the site merely to use such facilities.

Field Road System

The need for a field road system is often overlooked in planning with the result that some of the farm is inaccessible to farm machinery, the irrigation system is damaged by travel of farm machinery, or the roads are impassable after an irrigation. Provide roads above irrigation ditches and below field drains that are readily accessible for working the farm. Consider the following points in planning a farm road system.

1. Ease of operating the water-distribution system
2. Ready access to all areas of the farm for farm equipment
3. Transportation of farm produce from the fields
4. Dryness and usability of roads

Finances

Financing an irrigation system is the farmer's responsibility. But tell him the probable cost of the system selected before doing any detailed planning. He may not realize the cost involved and may find that he cannot finance the proposed plan. If so, plan to irrigate a smaller acreage at first, increasing the acreage as finances permit. Be certain that the initial development will fit in with the complete irrigation plan for the farm without costly alterations.

Physical Features

Permanent surface features, such as power lines, pipelines, conservation measures, etc., must be considered. Since power lines generally are expensive to move, plan to build the system around them. Determine location

and depth of pipelines or buried cables. Often they are limiting factors in land leveling or ditch building. If they are relatively shallow, they may be damaged or destroyed during construction. Maintenance of pipelines often damages an irrigation system by blocking borders or disrupting benches.

Windbreaks, orchards, fences, farmsteads, diversions, terraces, and similar obstructions greatly influence the layout. Usually fences can be changed, but other obstructions generally are fixed and the system must be built around them. If you do not allow for these features in planning, you may start the layout only to find that part of a field is so isolated it cannot be fitted into the irrigation system. This is especially true when irrigation systems are planned and installed on a piecemeal basis.

Adapted Methods of Water Application

Irrigation water application is commonly designated according to the manner in which water is applied to the soil. The three basic ways of applying irrigation water are

1. Sprinkler irrigation--the soil surface is wetted much as it is by rainfall.
2. Surface irrigation--water is applied by complete flooding or in furrows, wetting only part of the surface.
3. Subirrigation--water is applied beneath the surface, wetting the surface little if at all.

Methods of applying irrigation water vary with topography, soil conditions, amount of land preparation practical, crops to be grown, value of crops, cultural practices, and available water supply. Each method has certain limitations. Most can be adapted to a fairly wide range of conditions. On some sites several methods of water application are suitable. On other sites only one method can be used. In some areas farmers have become accustomed to particular methods of applying water and continue to use them even though others are more desirable and economical. Sound planning must also consider for each suitable method the cost and ease of installation, maintenance required, cost, labor and skill required for operation, and ease with which it can be fitted into the farm enterprise. To get acceptable irrigation efficiency, skill of the operator and flexibility of the system must be considered along with the irrigator's wishes in selecting the best method.

Sprinkler Irrigation

Water is sprayed into the air through a sprinkler nozzle and allowed to fall on the land surface in a uniform pattern at a rate less than the intake rate of the soil.

Sprinkler Method

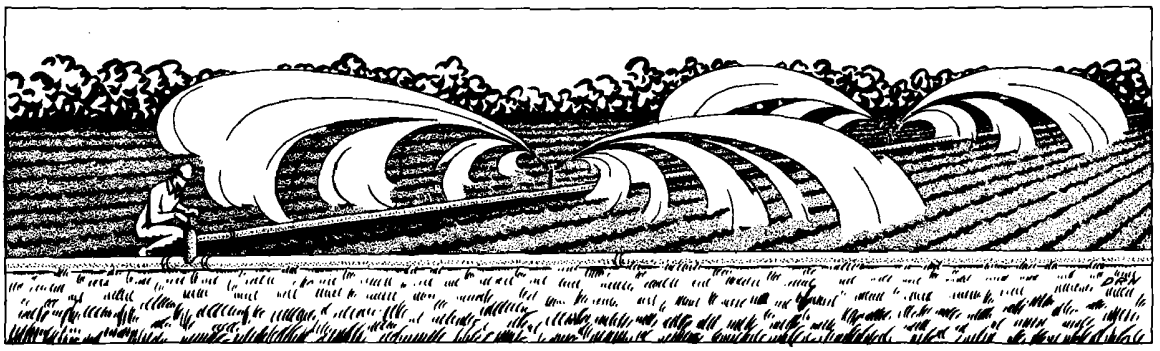
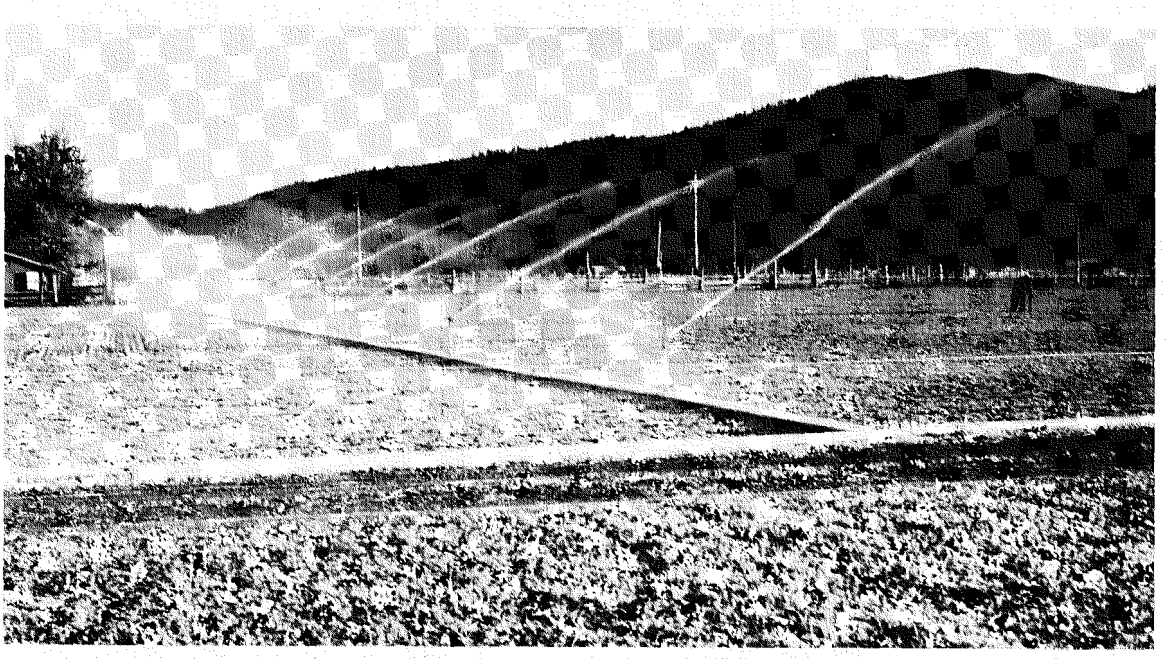


Figure 3-6.--Sprinkler irrigation.

Description.--Irrigation water is pumped from the source through pipes to the sprinklers and sprayed into the air (fig. 3-6). Two types of sprinkler systems are used to irrigate farm crops. In one, rotating sprinkler heads are spaced equally along the lateral lines. In the other, the lateral lines are perforated pipe. The lateral lines remain in one place until the required amount of water has been applied and are then moved the same distance for each successive setting. Perforated-pipe sprinklers deliver water through very small, closely spaced orifices in the pipe, provided fairly uniform distribution along both sides of the pipe.

Sprinkler systems can be semipermanent, having fixed main lines and portable laterals, or be fully portable in which both mains and laterals can be moved. In a solid-set system the entire field is served simultaneously by laterals lines. The main and laterals can be either located on the ground surface or buried for a totally permanent system.

Different kinds of sprinklers are shown in figures 3-7 to 3-14. Design criteria for sprinkler irrigation systems are discussed in chapter 11.



IDA-5048

Figure 3-7.--Hand-move sprinkler.

NEB-2139

Figure 3-8.--Big-gun sprinkler.

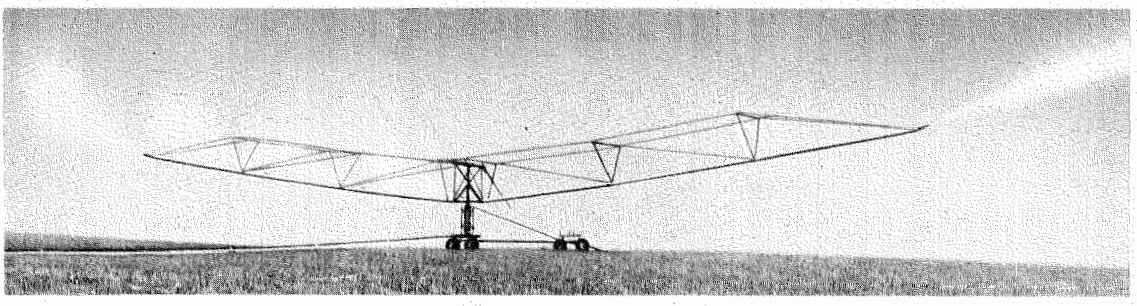


Figure 3-9.--Rotating-boom sprinkler.

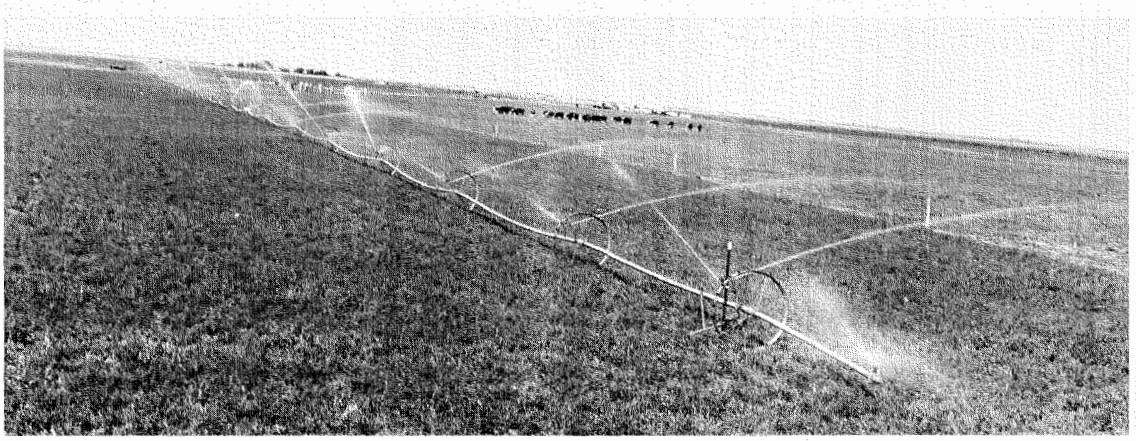


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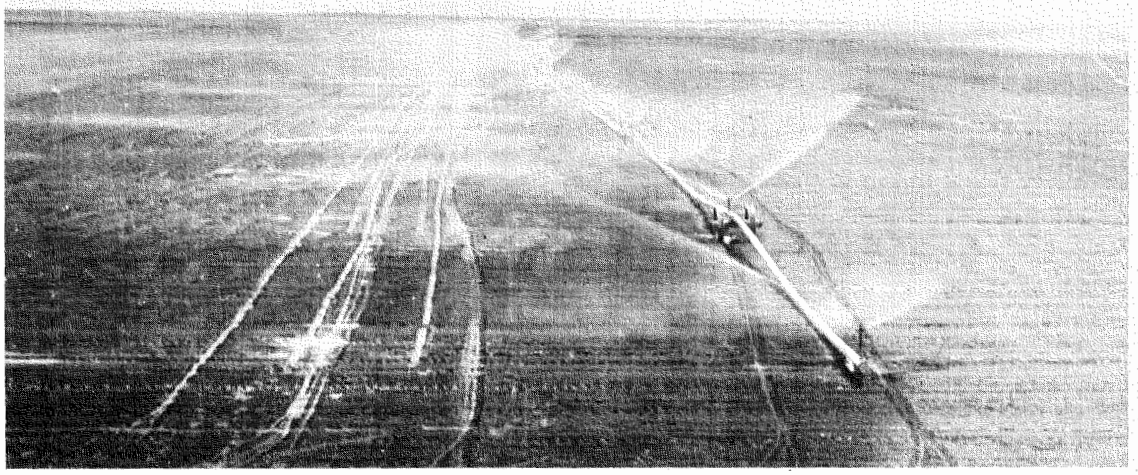
Figure 3-10.--Side-roll sprinkler.



NEB-2140

Figure 3-11.--Two-lateral sprinkler.

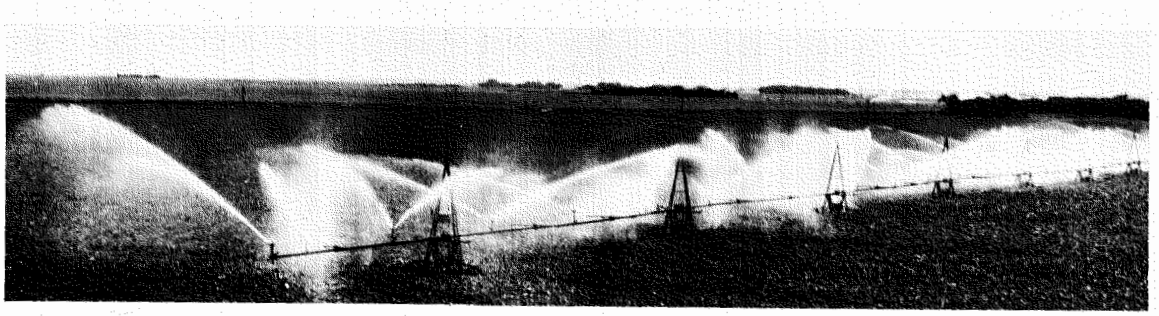


Figure 3-12.--Self-propelled sprinkler.

NEB-2142

Figure 3-13.--Solid-set sprinkler.

TEX-42802

Figure 3-14.--Perforated-pipe sprinkler.

Adaptability.--All crops except rice can be sprinkler irrigated. Sprinkler irrigation is suited to all soils having an intake rate higher than the rate of application. It is particularly suited to sandy soils that have a high intake rate. Soils too shallow to be leveled properly for other methods can be irrigated safely by sprinklers. Sprinkler irrigation can be used on any topography suitable for farming. It is especially suitable for steep slopes or irregular topography without extensive land preparation and for soils that cannot be leveled. If soil erosion is a hazard, sprinkler irrigation can be used in conjunction with mulching, terracing, and strip cropping.

Important Features.--Land leveling is not required. Some smoothing or grading is advisable if surface drainage is a problem or to provide a more uniform surface for seeding, tillage, and harvesting. Land too steep for efficient use of other methods can be irrigated safely. The cost of land leveling can be eliminated or greatly reduced. Small streams of irrigation water can be used efficiently, and well-designed sprinklers distribute water better than other methods. Surface runoff of irrigation water can be eliminated. The amount of water can be controlled to meet crop needs, and light applications can be made efficiently on seedlings and young plants.

Soluble fertilizers, herbicides, and fungicides can be applied in the irrigation water economically and with little extra equipment. Penetration of fertilizers into the soil can be controlled by applying the fertilizer at selected times during the application of water. Sprinkler irrigation can be used to protect crops against frost and against high temperatures that reduce the quantity and quality of harvest. It is the most efficient method for such protection. It may be necessary to add lateral lines and sprinklers for adequate temperature control.

Labor costs are usually less than for surface methods on soils having a high intake rate and on steep and rolling land. Sprinkler irrigation systems can be moved once or twice a day as a regularly scheduled part of the farm operation.

Limitations.--Wind distorts sprinkler patterns and causes uneven distribution of water. Ripening soft fruit must be protected from the spray. A stable water supply is needed for the most economical use of the equipment. The water must be clean and free of sand, debris, and large amounts of dissolved salts. Unburied mains and laterals may interfere with cultivation, spraying, and other farm operations.

The sprinkler method usually requires the highest initial investment of any method except where extensive land leveling is necessary for surface or subsurface irrigation. More special equipment subject to depreciation is needed. Power requirements are usually high since sprinklers operate with a water pressure of 15 to more than 100 pounds per square inch. Fine-textured soils that have a slow intake rate cannot be irrigated efficiently in hot windy areas. If water is applied at the low rate required for these soils, the percentage lost by evaporation and wind

drift increases. Cost of labor or equipment may be higher on fields that remain muddy for some time after an irrigation.

Surface Irrigation

Water is applied directly to the soil surface either by controlled flooding or in some kind of furrow. In controlled flooding the water applied to the surface is controlled by dikes and ditches. Graded-border, level-border, contour-levee, and contour-ditch methods are different types of controlled-flooding irrigation. In the furrow method, water is applied through regularly spaced large furrows, furrows between crop rows, or closely spaced small furrows or corrugations. In general, flooding methods are used for close-growing crops and furrow methods for row crops.

Graded-Border Method

Description.--Graded-border irrigation is a form of controlled surface flooding. The field to be irrigated is divided into strips by parallel dikes or border ridges (fig. 3-15), and each strip is irrigated independently. The border strips should have little or no cross slope but should have some slope in the direction of irrigation. Each strip is irrigated by turning in a stream of water at the upper end. The stream must be large enough to spread over the entire width between the border ridges without overtopping them. Usually the stream size should be such that the desired volume of water is applied to the strip in a time equal to or slightly less than that needed for the soil to absorb the net amount required.

Adaptability.--This method is suitable for irrigating all close-growing, noncultivated, sown or drilled crops, except rice and any other crops grown in ponded water. Legumes, grasses, small grains, and mint commonly are irrigated by this method. Graded borders also are used for irrigating orchards and vineyards.

Graded-border irrigation can be used on most soils. It is best suited to soils that have a moderately low to moderately high intake rate. Usually it is not used for coarse sandy soils that have a very high intake rate because of the stringent limitations on design. Nor is it well

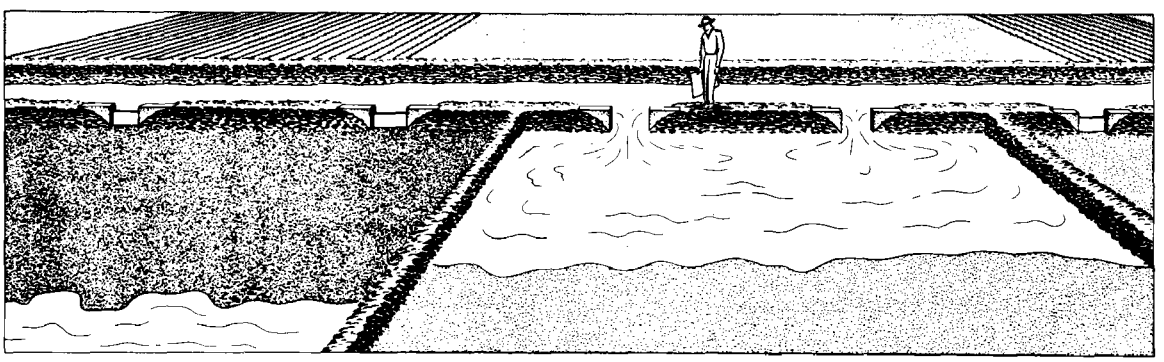


Figure 3-15.--Graded-border irrigation.

suited to soils having a very low intake rate since, to provide adequate intake time without excessive surface runoff, the irrigating stream may be too small to completely cover the border strips. This method is best suited to slopes of less than 0.5 percent. If erosion from rainfall is not a hazard, it can be used successfully on steeper slopes if the soil intake rate is not too low. For nonsodforming crops, this method is seldom used on slopes of more than 2 percent, but it can be used on slopes as steep as 4 percent for sod crops. In humid areas the maximum slope to be irrigated by this method is about 2 percent for sodforming grasses and 0.5 percent for other crops.

Important Features.--Good to excellent field application efficiency can be obtained if the borders are well designed and installed. Labor requirements are among the lowest for all application methods, and strip width can be designed to accommodate the farm machinery used for tillage, planting, and harvesting. If surface drainage is critical, the method is an excellent means for rapid disposal of excess surface water.

Limitations.--Topography must be relatively smooth or soils deep enough for adequate leveling. In some areas, land-leveling costs may be high enough to exclude using the graded-border method. The available irrigation stream must be large enough to irrigate a border strip of practical size. Young crops may be damaged or extra tillage required on soils that bake or crust after wetting. A light irrigation of less than about 2 inches is difficult to apply efficiently.

Level-Border (Basin) Method

Description.--This method is based on the rapid application of irrigation water to a level or nearly level area enclosed by dikes that retain the water at a uniform depth until it has been taken into the soil (fig. 3-16). Level borders are similar to basins, but basins generally are as wide as they are long and level borders are several times longer than wide.

An overall fall of 0.2 foot in the length of the border strip is often desirable as construction tolerance to avoid reverse grades. The stream of water turned into each border should be at least twice that required for the average intake rate of the soil. If the border is level, the

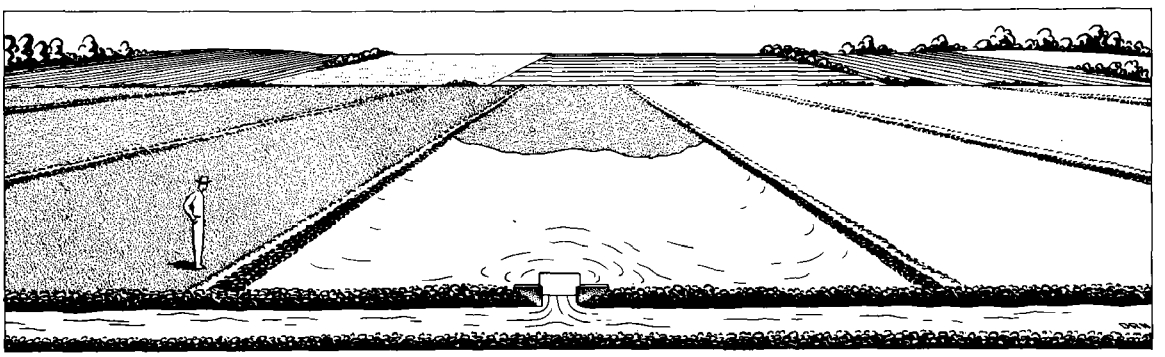


Figure 3-16.--Level-border irrigation.

irrigation stream can be turned in at any point or points around the border and at both ends if desired. If the border has a slight grade, the irrigation stream is applied at the upper end.

Adaptability.--This method is best suited to soils having a moderate to slow intake rate (2.0 intake family or less) and a moderate to high available water holding capacity. Although an efficient system for water application can be designed for soils that have a higher intake rate and a lower available water holding capacity, the borders are so small that they interfere with cultural practices and the location of delivery laterals.

Smooth, gentle, uniform land slopes are best suited to this method and give the best field layouts. One major advantage of this method is that it can be used to irrigate many different kinds of crops regardless of planting pattern. Crops such as carrots, which are adversely affected by flooding, can be planted in beds and irrigated with light applications in the intervening furrows. Row crops less susceptible to flooding can be flat-planted or bedded. Sown crops, drilled crops, and sod crops can be irrigated by using border furrows to guide the water. These wide variations can be accomplished without basic changes in layout or rate of application and still give high efficiency.

Important Features.--Many different kinds of crops can be grown in sequence without making major changes in design, layout, or operating procedures. Leaching can be accomplished without changing either layout or method of operation. Provisions for disposal or reuse of tail water are not needed although removal of excess rainfall may be necessary. Maximum use can be made of rainfall. No irrigation water is lost by runoff. This method can be adapted to automation easily or it can be operated efficiently by inexperienced labor. High application efficiency can be obtained.

Limitations.--Accurate land leveling is generally required. Border dikes must be high enough to keep the irrigation stream from overtopping the ridges. Border ridges may interfere with movement of farm machinery in border strips. On steep slopes requiring benching, drop structures, lined ditches, or pipelines may be required for adequate water control. In some areas special provisions must be made for surface drainage. In areas where wind velocity exceeds 15 to 20 miles per hour, it may be difficult to apply irrigation water if the wind direction is opposite to the direction of water flow in the border strip. Sets must be changed often. Maintenance of a level surface is essential to efficient operation, which may require changing tillage operations or using special tools, or both.

Contour-Levee Method

Description.--This method is a modification of the contour-border or basin method. Areas bounded by small contour levees and cross levees are completely flooded (fig. 3-17). Water applied at a rate considerably in excess of the intake rate of the soil spreads rapidly over the

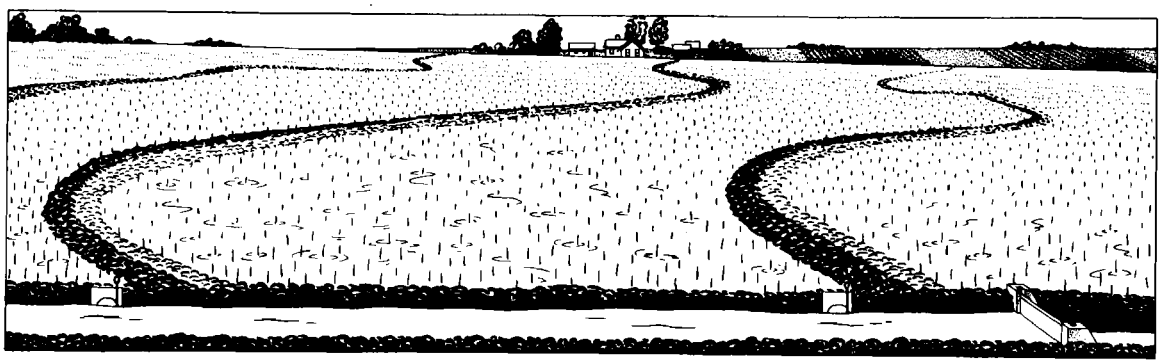


Figure 3-17.--Contour-levee irrigation.

area and is allowed to remain until it has infiltrated the soil to the desired depth. If the irrigation is for soil-moisture replenishment, the excess water is then drained off immediately. If the irrigation is for weed control on riceland, the water is impounded at a minimum depth of 3 inches and a maximum depth of 8 inches or less for several weeks.

Size of the unit area depends on the size of the available irrigation stream, soil intake characteristics, and topography of the field. Generally a stream of 1 cubic foot per second is required for each 2 acres for rapid flooding. Drainage is provided by placing pipe culverts in the drainageways through each levee. Water is held at the desired level by small weir-type spillways in the levees, allowing excess water from one area to spill over into the area immediately below.

Adaptability.--For successful contour-levee irrigation, soils should be medium to fine textured (0.5 intake family or less). For rice the soil should have a saturated permeability rate of 0.01 inch or less per hour or have a restricting layer of this rate just below the crop's root zone. The surface should be smooth and reasonably uniform and have a maximum slope of 1 percent, but slopes of less than 0.5 percent are preferred.

The contour-levee method is particularly suited to rice and can be used for irrigating cotton, corn, soybeans, small grains, pasture grasses, and hay crops. The crop to be irrigated must be able to stand in water for 12 hours or more without damage. Irrigation water must be available at a rate that permits rapid flooding of the areas enclosed by the levees. A minimum stream of 0.5 cubic foot per second per acre for the largest of the areas should be available.

Important Features.--Uniform distribution of irrigation water is easily obtained. A field application efficiency of 80 percent or more can be obtained with a well-planned and well-operated system. Although excess water must be drained, there is usually opportunity to reuse it on areas of lower elevation. Tail-water or runoff losses are limited to the water removed from the lowest area in the field. Since maximum use can be made of any rainfall, seasonal irrigation requirements are reduced to a minimum.

Adequate surface drainage facilities are an essential part of this system, and they can be provided at little extra expense. Generally the same facilities are used to apply water and to remove it. The amount of labor required is low compared with that required for most other methods. The controls are simple and easily operated, and irrigators with little experience can handle large irrigation streams. If only a moderate amount of land smoothing or leveling is needed, the initial cost is low compared with that of most other acceptable methods. The cost of water-control structures is comparable to that of the least expensive structures used in other surface methods.

Limitations.--This method is not generally suitable for use on soils of moderate to very rapid permeability. Irrigations of less than 2 inches are difficult to apply. Large irrigation streams are required. Irrigation water must be of good to excellent quality since the slowly permeable soils to which the method is suited accumulate salts rapidly and are difficult to leach. Land smoothing or leveling is usually required for uniform distribution of irrigation water, drainage, and operation of farm equipment. Many crops cannot be successfully irrigated if they are susceptible to damage by flooding at any stage of growth. Levees may be damaged extensively by waves if water must be applied before vegetation is established.

Contour-Ditch Method

Description.--Contour-ditch irrigation is a form of controlled surface flooding. Irrigation water is distributed from ditches running across the slope approximately on the contour (fig. 3-18). Water is diverted from the ditches by temporary dams. As the water rises, it is discharged through controlled openings in the ditch bank, by siphon tubes, or over a uniformly graded lower lip of the ditch. Water flows as an unconfined sheet down the slope from one contour ditch to the next, and runoff is collected in lower ditches for reuse. Water is applied to successive strips between ditches until the field has been irrigated. The width covered by each setting of the dams depends on the stream size available. A stream of 1 cubic foot per second usually covers a strip about 100 feet wide. The spacing between contour ditches (80 to 300 feet) is governed by topography, soil intake rate, and average net irrigation application.

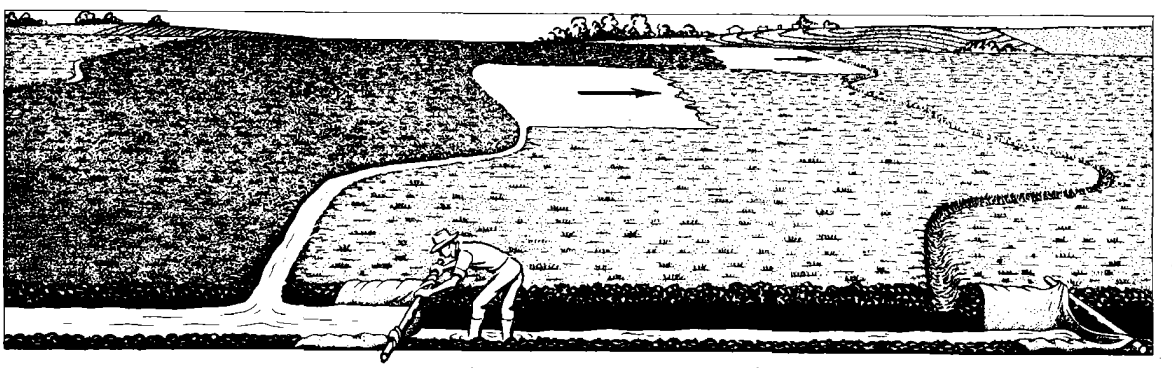


Figure 3-18.--Contour-ditch irrigation.

Adaptability.--This method is suitable for irrigating all close-growing, noncultivated crops except those grown in ponded water. Legumes, grasses, and small grains are the crops commonly irrigated by this method. Contour-ditch irrigation can be used for soils in the 0.1 to 3.0 intake families. Slowly permeable soils permit the widest spacing between ditches, and the application efficiency for a low net irrigation is high. Light-textured soils require close spacing of contour ditches, and the application efficiency is low.

This method is suited to slopes ranging from 0.5 to 15 percent. If erosion from rainfall is a hazard, the maximum slope is 4 percent. If soils and topography permit land leveling, contour ditches are seldom used on slopes of less than 1 percent. The maximum slope for moderately light to coarse textured soils is 4 percent. On slopes of 2 to 4 percent, if erosion from rainfall is a hazard, this method can be used only for sodforming crops.

Important Features.--Installation costs are among the lowest for all application methods. Little surface preparation is required on irregular topography. For annual crops the ditches can be easily filled to facilitate harvesting.

Limitations.--Irrigation efficiency is generally low. With careful management an application efficiency of 50 to 65 percent is possible. Small streams are not easily used. The spacing between ditches may vary considerably, causing different lengths of run. Extra labor is required for adjusting sets to get the proper depth of application and to reuse waste water. The close and irregular spacing between ditches hampers harvesting, especially of hay crops. Young crops may be damaged on soils that bake or crust. If rainfall erosion is a hazard, ditches cannot be installed until a crop is established, which eliminates the possibility of preplant irrigations.

Graded-Furrow Method

Description.--Graded furrows are small channels having a continuous, nearly uniform slope in the direction of irrigation (fig. 3-19). They are used in irrigating cultivated crops planted in rows. There are one or more furrows between crop rows except for bedded crops, in which the

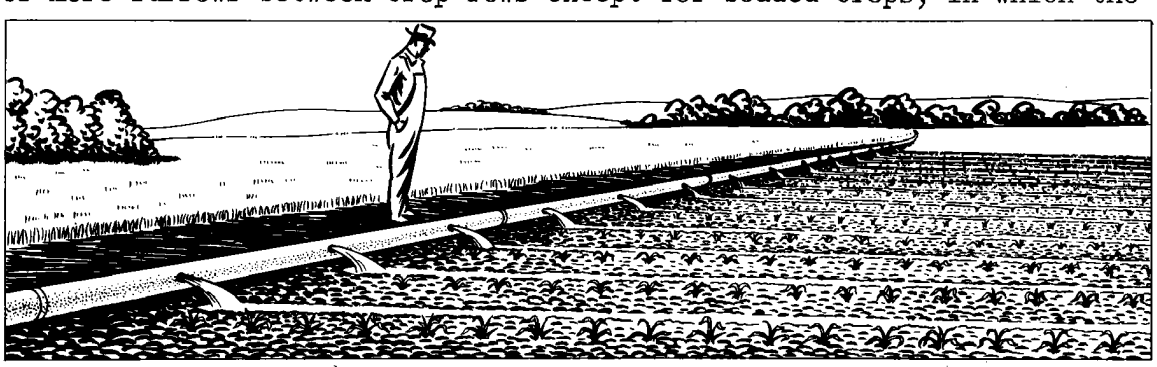


Figure 3-19.--Graded-furrow irrigation.

furrows are along each pair of rows. Size and shape of the furrows depend on the crop grown, equipment used, and spacing between crop rows.

Water flowing in the furrows soaks into the soil and spreads laterally to irrigate the areas between furrows. The length of time that water must be run in the furrows depends on the amount of water required to refill the root zone, intake rate of the soil, and rate of lateral spread of water in the soil. For most soils the initial irrigating streams must greatly exceed the intake rate to advance rapidly. Therefore, when water reaches the lower end of the run, the streams must be adjusted or cut back to prevent excessive waste from surface runoff or provisions must be made to recover tail water. But for low-intake-rate soils that crack when dry, it is not usually necessary to cut back the streams.

Adaptability.--The graded-furrow method can be used to irrigate all cultivated crops planted in rows, including orchard and vineyard crops as well as all field and truck crops. Graded furrows can be used on all soils except sands that have a very high intake rate and provide very poor lateral distribution of water between furrows. But they must be used with extreme care on soils that have high concentrations of soluble salts. To keep excessive amounts of toxic salts from accumulating in the areas between furrows, it may be necessary to use some surface-flooding method to leach salts from the root zone before this method can be used successfully.

This method is best suited to sites where the furrow grade does not exceed 1 percent. But in areas where erosion from rainfall is not a problem, the grade can be as much as 3 percent. In areas of intense rainfall, the furrow grade may need to be reduced to 0.5 percent or less to minimize the erosion hazard. On smooth, uniformly sloping fields, crops can be planted across the slope to reduce the furrow grade. Furrows also are used on graded benches built across the slope.

Important Features.--Both large and small irrigating streams can be used by adjusting the number of furrows irrigated at any one time to fit the available flow. Therefore any type of water delivery, from continuous flow to full demand, can be used. Field efficiency is high if water management is good. In areas where surface drainage is necessary, the furrows can be used to dispose of runoff from rainfall rapidly.

Limitations.--Labor requirements for the graded-furrow method are high. Flow into each furrow must be carefully regulated for uniform water distribution and minimum waste. Fields must be well leveled and facilities for collecting and disposing of surface runoff must be installed. Also, the method is not suitable for applying the very light irrigations needed for seed germination or for very shallow rooted crops grown on soils with a high intake rate.

Contour-Furrow Method

Description.--The contour-furrow method is similar to the graded-furrow method in that irrigation water is applied by furrows, but the nearly

level furrows carry water across a sloping field rather than down slope (fig. 3-20). The contour furrows are curved to fit the land surface. They have just enough grade to carry the irrigation stream. Head ditches or pipelines are run downhill or slightly across the slope to feed the individual furrows.

Adaptability.--This method can be used on most sloping soils except light sandy soils and soils that crack. The ridges between furrows in sandy soils may break and wash out, overloading the furrow below, which also breaks. This may continue all the way down the slope, causing heavy erosion damage. Soils that crack provide channels for water, causing similar downslope furrow breaks. This method is particularly suited to fields of uniform slope in both directions because most of the furrows can run completely across the slope and there need be few point rows.

The contour-furrow method can be used for nearly all cultivated crops planted in rows. In arid sections deep-furrowed row crops grown on medium- and fine-textured soils can be irrigated if the slope does not exceed 6 percent. On light-textured soils, the slope must not exceed 4 percent because of the danger of furrow breaks. For shallow-furrowed crops, the slope must not exceed 3 percent. For citrus and deciduous fruits, cane berries, vineyards, and nut trees, the slope can be steeper since the furrows are not disturbed by cultivation.

Important Features.--The contour-furrow method can be used to irrigate safely land too steep for downhill furrows, thus reducing the erosion hazard. Good distribution of water is possible because large irrigating streams can be used in the nearly level furrows and water reaches the end of the furrows quickly. This also reduces the time of irrigating. Good efficiency can be attained if the system is properly laid out and good water management practices are followed.

Limitations.--This method must be watched carefully to guard against furrow overflow and washout. In areas of intense rainstorms, rainfall probably causes more breakthroughs than irrigation water. The runs should be short enough to dispose of the runoff safely without breaking the furrow. Grassed waterways and structures are usually needed to carry

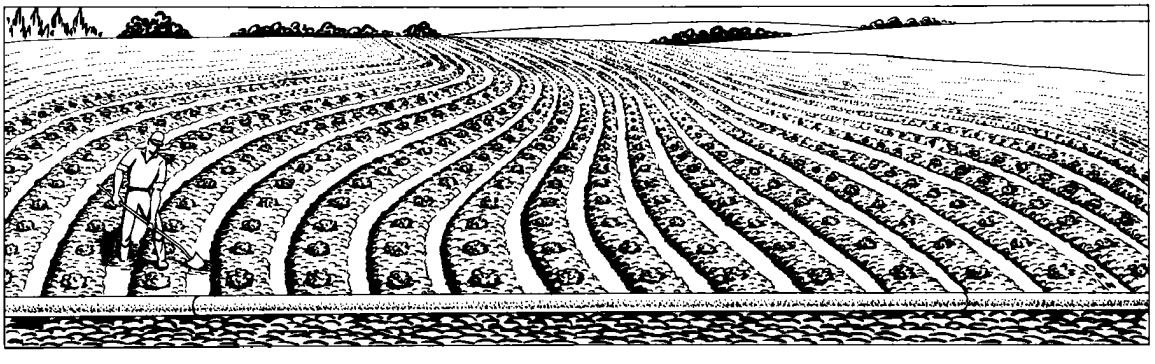


Figure 3-20.--Contour-furrow irrigation.

surplus water down the slope. For a crop like corn, all furrow breaks must be repaired by hand after the corn is laid by. Contour-furrow irrigation used in conjunction with parallel terraces provides additional insurance against breakthroughs.

Head and tail-water ditches must be protected because they run downslope and generally the grade is erosive. Considerable time is necessary to lay out a field, and planting and tillage must be done very carefully. Equipment used in planting, cultivating, and harvesting must turn on the crop at the end of point rows.

Level-Furrow Method

Description.--Level furrows are small channels without grade formed by farm equipment and used to irrigate crops planted in or between the furrows (fig. 3-21). The level-furrow method of water application requires the rapid introduction of irrigation water. A stream as large as the furrow can contain is turned into the furrow until the gross application has been made. The water, which is at uniform depth throughout the furrows, stands until absorbed by the soil. Lateral or capillary movement of water through the soil distributes the water to areas between furrows.

Adaptability.--The level-furrow method is best suited to soils having a moderate to slow intake rate (2.0 intake family or less) and a moderate to high available water holding capacity. The best field layouts for level furrows are on smooth uniform slopes. Row crops are the crops most easily irrigated by level furrows, but drilled or sown crops can be irrigated effectively if the soil has been furrowed and ridged before planting. In areas where rainstorms occur in such intensity and duration that the water-storage capacity of the furrow may be exceeded, border dikes are also needed.

Important Features.--The amount of water applied can be adjusted to meet seasonal variations by changing duration of application or size of furrow stream, or both. No change in layout is needed. High application efficiency can be obtained with this method if it is properly designed and operated. No irrigation water need be lost through runoff.

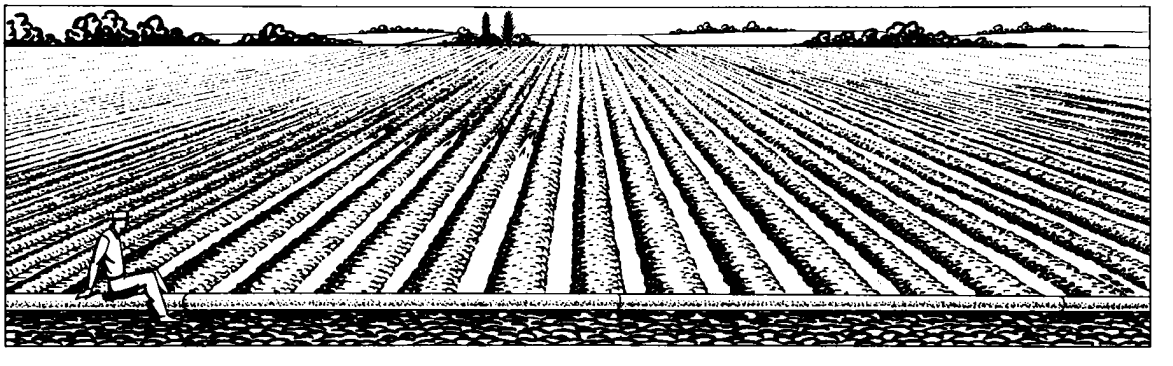


Figure 3-21.--Level-furrow irrigation.

Unless winds of high velocity affect the advancing stream, the field ditches or other conveyance structures can be spaced at twice the design furrow length since water can be introduced at both ends of the furrows. This reduces cost of constructing and maintaining the delivery system, and farm machinery can travel farther before turning. Maximum use can be made of rainfall even if storm intensity exceeds the intake rate. Provisions for disposal or reuse of tail water are not needed. Leaching can be easily accomplished. This method can be automated easily.

Limitations.--In areas where wind velocity exceeds 15 to 20 miles per hour, it is difficult to apply irrigation water if the wind direction is opposite to the direction of water flow in the furrow. Since wind erosion is usually a problem in such areas, row and furrow length should be normal to the prevailing wind direction if practical. If the furrow length is parallel to the prevailing wind direction, water should be applied at the upwind end of the furrows.

Furrow capacity must be large enough to control stream flow. Furrows should be able to contain approximately one-half the volume of the net irrigation application. Sets must be changed often. For efficient operation of a system using this method of water application, it is essential that tillage operations maintain the surface topography and the furrow shape and cross section.

Corrugation Method

Description.--Corrugation irrigation is a partial surface flooding method. Irrigation water does not cover the entire field but is applied in small channels or corrugations evenly spaced across the field (fig. 3-22). Water flowing in the corrugations soaks into the soil and spreads laterally to irrigate the areas between corrugations. The corrugations should be spaced to permit an adequate lateral spread by the time the desired amount of water has infiltrated the soil.

The length of time that water must be run in the corrugations depends on the amount of water required to refill the root zone and on the intake rate of the soil. Initial irrigating streams must greatly exceed the intake rate of the soil in order to advance rapidly. Therefore, when water reaches the lower end of the run, the streams must be adjusted

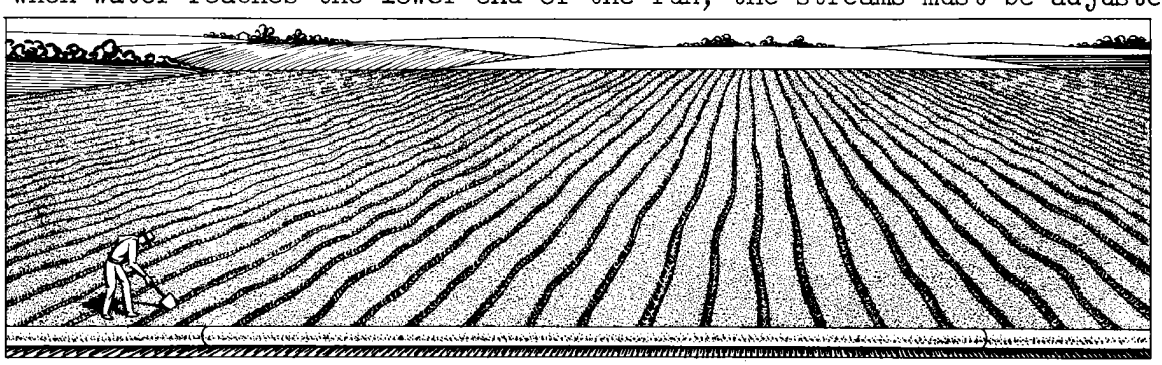


Figure 3-22.--Corrugation irrigation.

or cut back to prevent excessive waste from surface runoff or provisions must be made to recover tail water.

Adaptability.--Corrugation irrigation is best suited to areas of low rainfall and smooth fields that have slopes between 1 and 8 percent. It can be used on irregularly sloping sites, but the corrugations must have a continuous slope in the direction of irrigation and the cross slope must be such that breakthroughs from both irrigation water and rainfall runoff are held to a minimum. The cross slope usually should be considerably less than the slope in the direction of irrigation. The use of corrugations in humid areas usually creates a serious erosion hazard.

All close-growing, noncultivated sown or drilled crops except rice and other crops grown in ponded water can be irrigated by this method. Legumes, grasses, and small grains are commonly irrigated by this method, which is used also for irrigating noncultivated orchards and vineyards having grass or legume cover crops.

Corrugations are best used on fine to moderately coarse textured soils. They are not suitable for coarse-textured high-intake-rate soils or saline soils. The method is especially good for irrigating soils that bake or crust. Since only a small part of the soil surface is wetted, crusting is greatly reduced. Corrugations often are used in establishing crops to be irrigated by the graded-border method later.

Important Features.--Irrigating streams can be large or small since the number of corrugations irrigated at one time is simply adjusted to fit the available flow. Little land preparation need be done, and often new land can be cleared and put into production the first year. On well-leveled fields reasonably high efficiency can be obtained easily if proper water management practices are followed.

Limitations.--Labor requirements are high. Irrigation streams must be carefully regulated for uniform water distribution and minimum waste. Fields must be corrugated at least once every year and in many cases, more than once. Equipment operating costs also are high. The rough field surface is difficult to cross with equipment and causes excessive damage from vibration. In addition, the method is not well suited to gentle slopes. Seldom should it be attempted on slopes of less than 1 percent. Therefore it is not generally suited to areas that have high rainfall during the irrigation season.

Subirrigation

Water is applied beneath the ground surface to create an artificial or perched water table over some natural barrier that restricts deep percolation. Moisture then reaches the plant roots through capillary movement.

Subirrigation Method

Description.--Irrigation water is introduced through open ditches, tile drains, or mole drains (fig. 3-23). The water table is maintained at some predetermined depth below the ground surface, usually 12 to 24 inches, depending on the rooting characteristics of the crop grown.

Open ditches are probably most widely used. Feeder ditches are excavated on the contour and spaced close enough to insure control of the water table. They are connected to a supply ditch that runs down the predominant field slope and has control structures as needed to maintain the desired water level in the feeder ditches.

A tile system is expensive and generally is used only for high-value crops. Parallel tile lines are laid 24 inches to 40 inches deep at a nearly level grade that approximately parallels the ground surface. They are spaced close enough to insure almost complete control of the water table. In general the upper ends of these feeder lines are connected to a supply line into which water is introduced. The lower ends are connected by an outlet tile which is used to carry excess irrigation water and storm water to a satisfactory outlet. Controls are placed in each feeder line to regulate the water-table level.

Mole drains have been used successfully as feeder lines only in organic soils. They are formed by pulling a bullet-nosed cylinder through the soil at a minimum depth of 30 inches to prevent closure of the holes by compaction during farming operations. The lines are 12 to 15 feet apart and are connected by an open ditch that serves both to introduce irrigation water into the mole drains and to remove water from them for drainage. Well-constructed moles in suitable soils give effective service for 5 to 8 years.

Adaptability.--The subirrigation method is suited to soils having reasonably uniform texture and permeable enough for water to move rapidly both horizontally and vertically within and for some distance below the crop's root zone. The soil profile must also contain a barrier against excessive losses through deep percolation, either a nearly impermeable layer in the substratum or a naturally high water table on which a perched or artificial water table can be maintained throughout

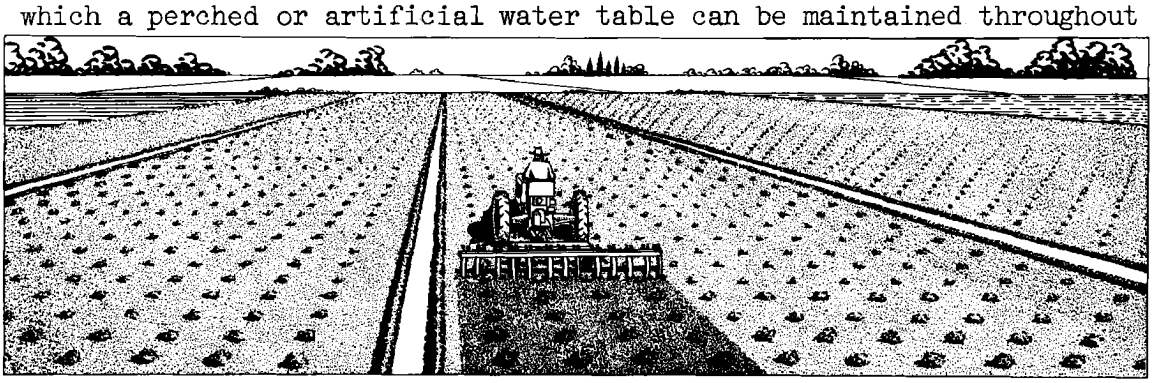


Figure 3-23.--Subirrigation.

the growing season. Topography must be smooth and nearly level or the slopes very gentle and uniform. The subirrigation method is suited to irrigating vegetables, most field crops, small grains, pasture grasses, most forage crops, and flowers.

Important Features.--This method can be used for soils having a low water-holding capacity and a high intake rate where surface methods cannot be used and the cost of sprinklers is excessive. The water level can be maintained at optimum depths for crop needs at different growth stages. Water loss by evaporation from the soil can be held to a minimum. Weed seeds are not carried over the surface by irrigation water.

The subirrigation distribution system can also be used as the drainage system. Tile feeder lines generally provide better drainage than open-ditch feeder lines. Labor requirements are less than for any other irrigation method. Labor is required only for regulating stream flow into the system, regulating water-level control structures, and tending the pump if pumping is required.

Limitations.--Since this method requires an unusual combination of natural conditions, it can be used in only a few areas. Water having a high salt content cannot be used. In some arid areas soils become saline unless adequately drained. Choice of crops is limited in some areas. Deep-rooted crops such as deciduous orchard trees and citrus trees generally cannot be subirrigated.

Irrigation Water Conveyance

Irrigation water must be made available to each part of the farm irrigation system at a rate and elevation that permits proper operation of the selected methods of water application. Irrigation water should be conveyed as economically, efficiently, and safely as possible. The delivery part of the farm irrigation system must be large enough to furnish the required irrigation water to meet crop demands during peak-use periods. If the water is delivered on a rotation or turn basis, the system must be large enough to allow delivery of the water in the time allotted. Plans should provide for future needs and expansion.

The type of conveyance facilities varies with the method of application. Sprinklers require pressure pipe, mains, and laterals, and subirrigation uses either ditches or tile. The contour-levee method generally uses a head ditch and levees, and the furrow and border methods require either ditches or pipelines with siphon tubes, gated pipes, or other forms of takeouts.

Conveyance facilities generally are either surface ditches with all the necessary grade-stabilization and water-control structures or pipelines. They must be accessible for operation and maintenance. They must be able to provide water to every part of an irrigated area. They should be located so that they interfere with farming operations as little as is practical.

Ditches

Irrigation ditches are open channels used to carry irrigation water to its point of use. They are used more than any other type of conduit. Small inadequate ditches without proper control structures and maintenance probably are the source of more trouble in operating an irrigation system than any other cause.

Ditches that carry irrigation water from the source of supply to one or more farms are known as canals and laterals. They are generally large and should always be permanent installations. Field ditches convey water from the farm source of supply to a field or fields within the farm unit. They also should be permanent installations.

Head ditches are used to distribute water in a field for surface irrigation. They are laid out at the high end of the irrigation run and are generally perpendicular to the direction of irrigation for furrows and borders. In contour-ditch irrigation and in subirrigation where water is distributed through open ditches, the head ditch runs down the slope and water is released on one side or both. Head ditches can be permanent or constructed each irrigation season. The water surface in head ditches should be above the ground level, 0.5 to 1 foot higher than the ground to be irrigated. If possible, the ditches should be nearly level (less than 0.1 foot fall per 100 feet) so that water can be backed up for a maximum distance, thus requiring a minimum of check dams and labor to control irrigation flow.

Ditches work best in clay or loam soils since seepage is usually less and ditch banks are more stable than those in sands or sandy loams. Open ditches can carry large volumes of water and have the advantage of low cost per volume of water carried. On soils where seepage is not a problem, they are easy to build.

Ditches have some limitations. Losses from seepage and evaporation can be high, and weeds and burrowing animals can cause trouble. Ditches take up valuable space and may hinder farm operations. Their maintenance requirements are higher than those for pipelines.

Unlined Ditches

Unlined ditches are the most commonly used method of carrying irrigation water, but many are not efficient. Small ditches can be easily built and maintained with farm equipment. They can be built before the irrigation season starts and be removed before harvest, or they can be removed after each irrigation and new ones built for the next irrigation.

In porous soils unlined ditches lose considerable quantities of water by seepage. Soil permeability probably is the most important factor. Losses are greater if the water is carried a long distance and are proportional to the wetted perimeter and depth of water flow in the ditch. Vegetation along a ditch, particularly along permanent ditches,

contributes to water loss through transpiration. Rodents and insects cause losses by burrowing in ditch embankments. In addition to the loss of irrigation water, seepage also damages adjoining land by raising the water table.

Grade-control structures are required in ditches if the design flow develops an erosive velocity. On slopes where drop structures must be closely spaced, it may be more economical to use a lined ditch, chute, or buried pipeline. Where ditches cross roads or waterways, it is necessary to install some type of crossing structure.

Lined Ditches

Ditch lining is an effective way to control seepage. Erosion-resistant linings can be used also to control ditch-bottom and bank erosion. For any given flow, lined ditches can be smaller than unlined ditches, which reduces the amount of land they take up. Lining also provides some protection against damage by rodents. Lining protects land against waterlogging and salinity. Depending on the kind, a lining reduces cost of maintenance, insures against interruption in water deliveries, and helps control weeds.

Selecting a lining should be governed by availability of the material and equipment needed to install it, ditch size, climatic and foundation conditions, and whether the irrigation stream is continuous or intermittent. Freezing and thawing damage some kinds of linings as does trampling by livestock and a fluctuating water table. Vegetation will damage some linings unless growth is controlled.

Many kinds of materials are used. Concrete is probably the most popular, but asphaltic materials, membranes, metals, chemical sealants, and impermeable earth materials are also used. Any of these materials make good linings if they are properly selected and are installed according to site conditions.

Concrete Lining.--Portland cement concrete is one of the most widely used materials. If site conditions are favorable, a well-constructed concrete lining gives long service with minimum repair and maintenance costs. Nonreinforced concrete is generally used. Thickness ranges from 1-1/2 to 3 inches, depending on climate and the expected water velocity in the ditch.

Concrete linings withstand high stream velocities and therefore are particularly suitable for erosion control as well as seepage prevention. They are superior to most other linings in resistance to mechanical damage. They are limited to nonexpanding soils where it is possible to get good internal drainage. If concrete linings are to be installed on poorly drained sites, in areas subject to severe frost heaving, or in soils having a high sulfate-salt concentration, they must be specially designed and protected.

If good concrete is available locally, slip-form-placed portland cement concrete is probably the most economical lining (fig. 3-24). In this method concrete is placed by a specially designed machine. The slip form rides on and is guided by the subgrade as it is pulled forward by a tractor or winch. Freshly mixed concrete is poured through a hopper so that the slip form distributes concrete to the sides and bottom of the ditch. The rear section of the slip form is a strike-off or screening mechanism. Thickness of the concrete lining is determined by the difference in height between the bottom of the rear section and the bottom of the front section. Ready-mixed concrete is probably best to use because its quality is easy to control and sufficient volume can be available at all times to keep the form in operation as continuously as possible.

For a farmer who wishes to dig and line his own ditches, panel-formed lining has advantages. After digging the ditch to grade, he sets guide-form panels about 10 feet long and pours concrete in every other panel, skipping a 10-foot section (fig. 3-25). When the concrete is set, he moves the guides and pours the skipped panels. The bottom in each section is poured first, and then the fresh concrete is screeded up the slope.

Pneumatically applied mortar known as shotcrete is sometimes used to line and resurface old concrete and rock cuts. Special machines are required, and the concrete mix must be carefully controlled. It is possible to get a strong durable lining but, except for very thin linings, it is more costly than slip-form concrete.

Asphalt Lining.--Asphalt can be used for seepage-control linings, either as asphaltic concrete or in sheets, planks, or membranes. Asphaltic concrete consists of sand and gravel bound together with asphaltic cement. It is similar to portland cement in many respects, but it does not last as long and withstands lower velocities. Asphaltic concrete is not so hard as portland cement concrete and is therefore more subject to mechanical damage. In many places the subgrade must be sterilized to prevent vegetation from growing through the lining and causing deterioration. Hot-mix asphaltic concrete has given fairly satisfactory results, but special equipment is needed to blend and place it. It can be placed by a slip form or heated screed moved slowly along the ditch by winch or tractor.

Prefabricated asphalt planks are also available for lining ditches. They are 2 to 4 feet wide by 8 to 12 feet long and one-fourth to one-half inch thick. They should be laid in warm weather so that they soften enough to conform to the shape of the ditch. Generally they are installed transversely. But if they are lapped, the lap is downstream so that water puts no stress on the joints. If the sheets are butted, a cap strip is used to cover the joints. Planks should be buried in the berm for anchorage. Unless the lining is well anchored, it sags on the slope and wrinkles.

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Figure 3-24.--Placing concrete ditch lining by slip-form method.

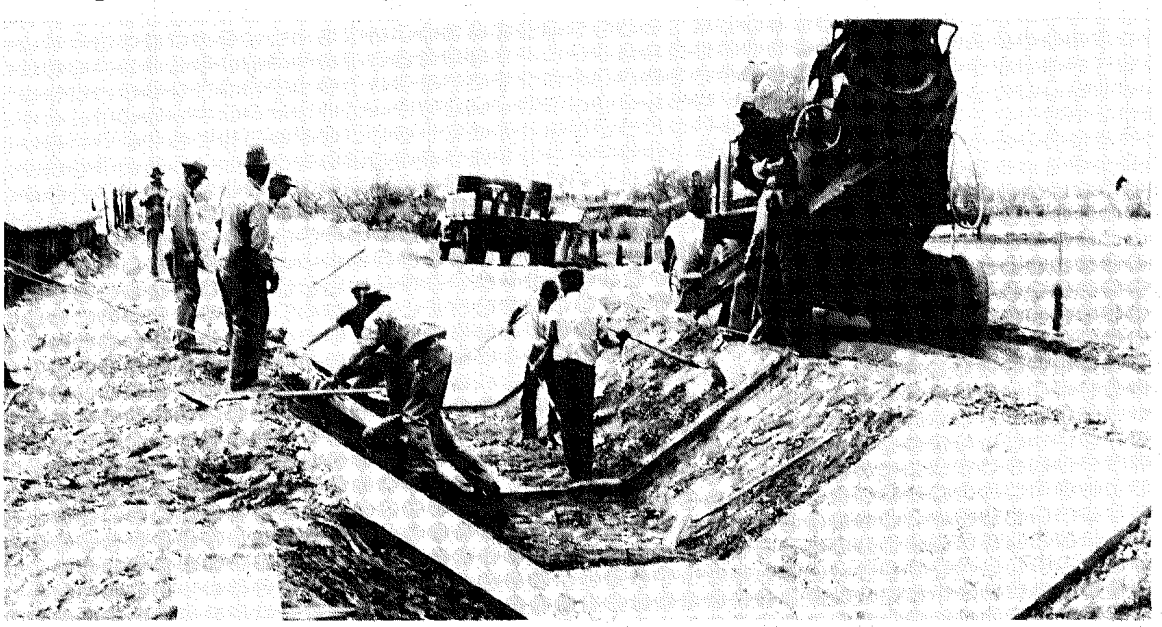

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Figure 3-25.--Constructing concrete ditch lining by alternate-panel method.

Prefabricated asphalt-membrane linings can be installed in small irrigation ditches by unskilled labor. The liners are one-eighth to one-fourth inch thick and come in rolls 40 inches wide. They are designed to be handled and placed in much the same manner as rolled roofing with lapped and cemented joints. These linings are usually covered with earth and gravel, but if the irrigation stream is to have a high velocity, they can be covered with shotcrete or macadam. The liner is buried in a trench on the berm paralleling the ditch to hold the liner in place. Various kinds of asphalt-membrane linings are available, such as asphalt-coated jute, asbestos fiber with asphalt coating, fiber-glass mat filled with asphalt, or other organic materials saturated and coated with asphalt.

Asphalt lining can be sprayed on. The cross section of the ditch is made larger than required. The asphalt is then sprayed over the ditch and covered with 6 to 9 inches of protective earth covering. Sprayed-on lining can be used only in ditches having a stream velocity of 3 feet per second or less. Special equipment is required for spraying the hot asphalt. If properly installed, sprayed-on lining will give reasonably good service for at least 10 years.

Flexible-Membrane Lining.--Strips of a specially formulated film in sheet form, usually rubber or plastic, can be joined with an adhesive and used as a ditch lining. The subgrade should be firm, smooth, and free of vegetation. All sticks, clods, and debris should be removed to protect the lining against punctures.

In permanent ditches the membrane generally is buried, which lengthens its usable life. The ditch is overexcavated, and the lining is placed and then covered with soil or gravel. The covering material must be carefully selected and placed on the membrane so that there is no damage during construction. Flexible membranes can be used only in ditches in which the stream velocity does not exceed 3 feet per second. The earth covering, 6 to 9 inches thick, serves to weight the liner and hold it in place when the ditch is not filled with water as well as to minimize mechanical damage. Since weeds may pierce a plastic lining, a sterilizing agent is used on the subgrade before the membrane is placed. Butyl rubber resists deterioration due to exposure, biological activity, and root penetration. Maintenance work must be done very carefully to keep membrane linings from being damaged.

Prefabricated Metal Lining.--Prefabricated metal liners can also be used to control seepage and erosion in irrigation ditches. They come in convenient lengths for easy handling. The sections are battened together, and a special sealant is used to make all joints watertight. These liners have an advantage in isolated areas where it is difficult to bring in other kinds of lining material. They should provide many years of trouble-free service, and construction and maintenance costs are low. But they should not be installed in areas in which the water has a high concentration of salt or other chemicals injurious to the metal without a coating specifically formulated to protect them from these chemicals.

They are suited to small ditches that have a bottom width of no more than 3 feet. The bank of the ditch should be high enough for the top edge of the lining to be firmly anchored in the ditch bank. Weeds are no problem, and the liners are resistant to tunneling by burrowing rodents. If freezing temperatures are common, the foundation must have adequate drainage to prevent water accumulating under the lining.

Chemical Sealants.--Chemical sealants can be used to make ditch subgrades nearly impermeable to seepage. They are effective if the ditch perimeter is moist most of the year but are less effective if the ditch dries out. Cracking of the soil breaks the membranes formed by the sealant and provides channels for seepage.

Chemical sealants can be used on any soil but are not particularly suited to sandy soils. Some are not satisfactory because of short life, high cost, or toxicity to animals and crops. These sealants are waterborne and therefore must be put in the ditch water, usually at a point of disturbance such as a drop structure to facilitate mixing the sealant with the water. Some supplemental mixing may be required.

One application method is to put the sealant into a flowing ditch with the water checked at a ditch structure to reduce the velocity of flow. This allows more time for the sealant to act on the subgrade in a given reach than is possible under normal flow. Ponding is another method. Treated water is allowed to stand in successive ponds formed in a ditch by temporarily sealing ditch structures or by placing temporary dams between structures. The water is allowed to remain in each pond long enough for the sealant to act on the soil. Although this method may be more costly, the sealing effect is somewhat better than that of the flowing-water method.

Bentonite.--Bentonite is a low-cost material similar in appearance to ordinary ground clay. It swells 12 to 15 times its dry size when wet and fills the voids through which water seeps. The three general methods of using bentonite for sealing ditches are by membrane lining, soil-mix lining, and sedimenting.

In the first method bentonite is spread as a membrane, 1 to 2 inches or more thick, over the canal subgrade and then covered with a 6- to 12-inch protective blanket of stable earth or gravel. If properly placed, the membrane lining controls seepage for many years.

In the soil-mix method, bentonite is spread evenly over the perimeter of the ditch and then mixed with the upper 3 to 6 inches of soil by disk, spiked-tooth harrow, or rake. The treated soil is then rolled or tamped until a good soil density is obtained. In some places a protective cover of stable earth or gravel is applied.

In the sedimenting method, bentonite is applied in one of three ways. It can be scattered over the surface of the water, dumped into the ditch at intervals before the water is turned in, or put into the ditch water

as slurry. The bentonite swells, and the resultant gel fills the voids along the sides and bottom of the ditch. Since it does not penetrate the soil to any depth, it forms a thin coating on the wetted perimeter of the ditch, which reduces seepage. But since bentonite shrinks on drying and is eroded by flowing water, the coating does not last very long.

Earth Linings.--Linings of natural or processed soils often prove economical for reducing seepage and stabilizing sections if suitable materials are available from the ditch excavation or from nearby borrow areas. Compacted earth linings are easily damaged in ditch cleaning and by vegetation, but under ordinary circumstances their initial installation cost is less than that of other types of linings. There are three general kinds of earth linings: Thick compacted earth, thin compacted earth, and material compacted in place. For thick or thin compacted earth linings the porous earth in the ditch must be removed and then replaced by material more suitable for ditches.

A thick compacted earth lining generally is 2 to 3 feet thick, measured normal to the side slope, and 1 to 2 feet thick on the ditch bottom. Because of the cost, thick compacted linings generally are used for large canals and ditches, but in some places they are economical for medium-size and small ditches.

A thin compacted earth lining generally consists of a 6- to 12-inch layer of thoroughly compacted cohesive soils. The lining commonly is covered with a 6- to 12-inch layer of coarse soil or gravel. Thickness of both lining and cover varies with the kind of soil used and the velocity of the water to be conveyed. Soils used for thin compacted linings are gravels with sandy clay binder, clay gravels, sand with clay binder, and clayey sands.

In some places it is possible to compact soils in the ditch banks and bottom enough to reduce seepage losses appreciably. Many fine soils and well-graded coarse soils and fines can be compacted in place. This is particularly true if soils have a fractured structure. Compaction is accomplished by scarifying, adding moisture, and compacting to the required density by sheepsfoot rollers, flat rollers, or other available equipment. The soil should be tested in a laboratory to determine moisture and density requirements and the feasibility of compaction to eliminate seepage.

Conveyance Structures

Flumes, inverted siphons, elevated ditches, road culverts, and bridges are used to carry water across swales, draws, and roads and along steep hillsides. These structures are necessary to transport irrigation water efficiently.

Flumes.--Flumes are artificial channels supported by substructures, which carry water across areas where ditches are not practical, such as draws or swales or along steep or rocky hillsides. They must be big

enough to carry the full discharge of a ditch, and the substructures must be strong enough to support the channel when it is filled with water.

Timber, metal, or concrete ordinarily are used for open flumes. Pipes can be used for closed flumes. Metal or concrete flumes generally are preferred over timber flumes (fig. 3-26). They can be made almost watertight and remain so during their usable life if the supporting structure is well designed to prevent any sagging or shifting of the channel. Reinforced-concrete flume channels are the most nearly permanent as well as the most costly. They also require concrete substructures. Metal pipe flumes are particularly suited to small flows. They can be installed quickly, and some of the dangers of overflow possible in open flumes are eliminated. A pipe flume has the disadvantage that it may be plugged by floating debris.

Substructures commonly are built of timber, steel, or concrete. Timber substructures should be treated with a preservative to extend their life. Concrete or steel substructures generally have a longer service life, need less maintenance, and are not easily damaged by fire.

Inverted Siphons.--Inverted siphons are closed conduits with each end raised, forming a U-shaped structure, that are used to carry water across depressions and drains or under roads and other obstructions (fig. 3-27). They are usually made of corrugated or smooth metal pipe, concrete pipe, or reinforced concrete poured in place. They are particularly suited to conveying water under roads if the water in the ditch is carried above ground. They are often used in place of flumes, particularly for crossing steep wide depressions. They differ from culverts in that the top of the pipe is lower than the water surface and the pipe is always under some pressure. The amount of water they can carry depends on the size and kind of conduit and on the difference in elevation between the water surface at the inlet and at the outlet. Velocity in the pipe should be at least as high as that in the ditch leading to the structure to prevent sedimentation at the bottom of the siphon. Trash racks are needed to keep the siphon open. Properly installed inverted siphons require little maintenance. Since they are underground, they are well protected, especially against flood damage.

Elevated Ditches.--Elevated ditches are open channels built on compacted earth fill to convey water across shallow depressions or to deliver water by open ditch to a high part of a field. The fill material must compact readily but not crack when dry. Elevated ditches generally are used for carrying large flows or in places where they are less costly than flumes, siphons, or pipelines.

The major problems are seepage loss, dry-weather cracks through the ditch bank, difficulty of controlling weeds and rodents, and difficulty of maintenance. For these reasons it is generally best to use pipe conduits if the ditch must be elevated more than 2 or 3 feet. Careful and timely maintenance is necessary because a break in the bank may

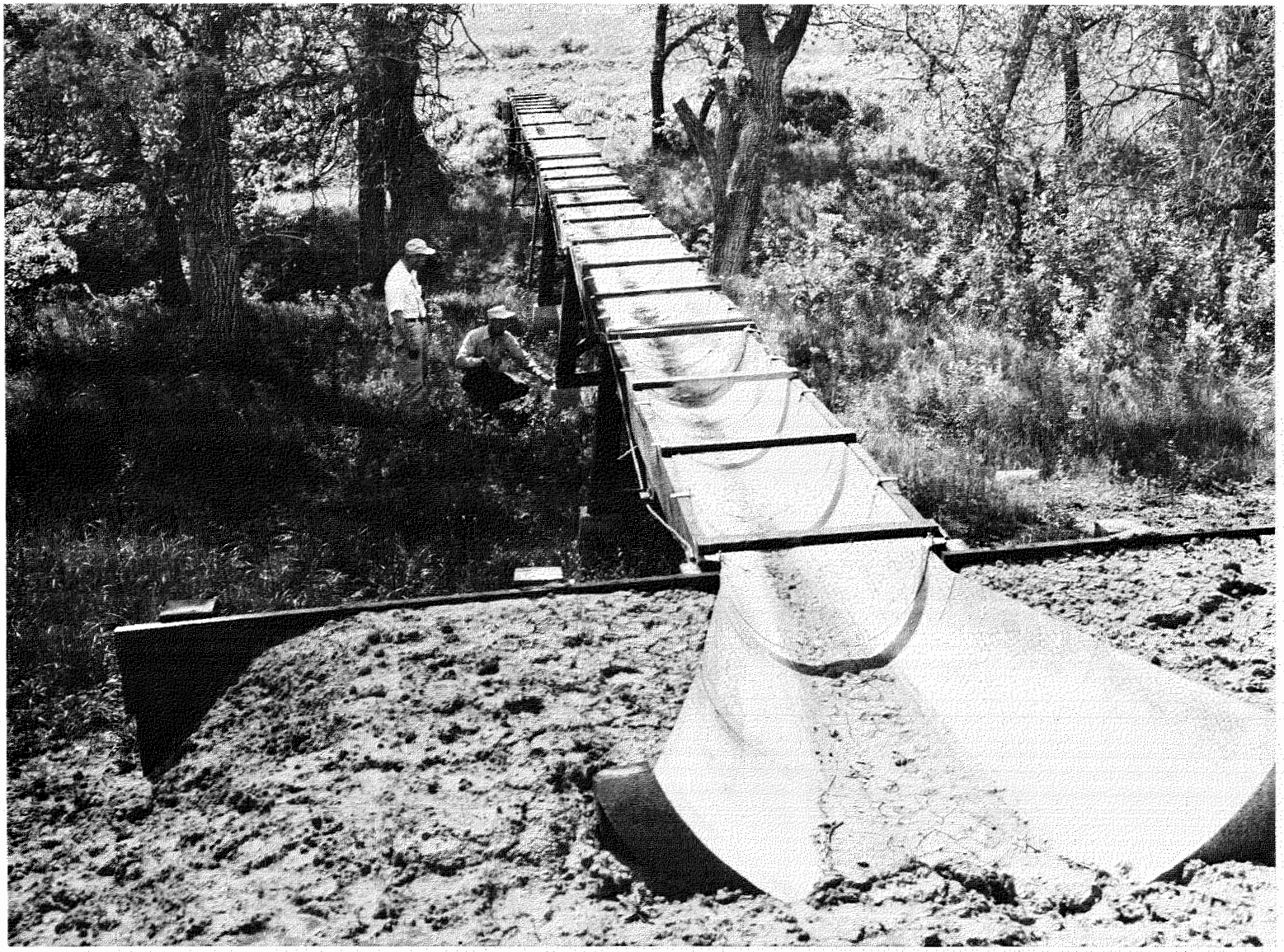

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Figure 3-26.--Timber-supported metal flume.

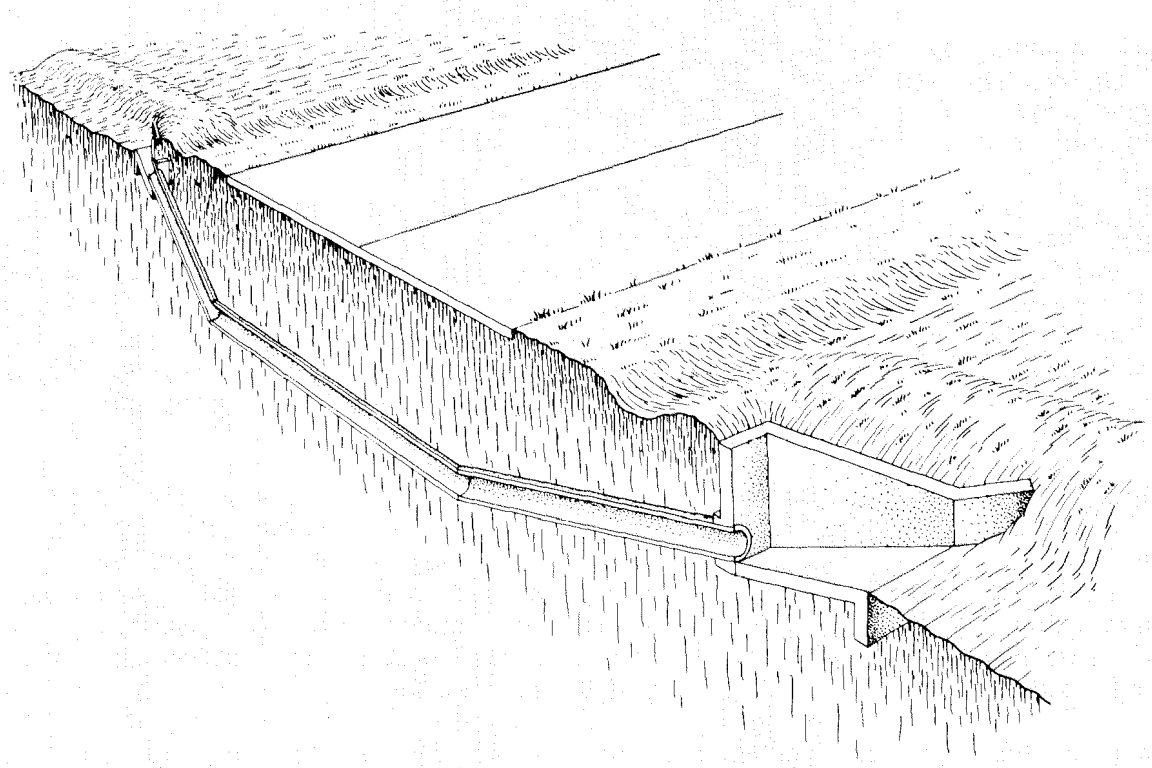


Figure 3-27.--Section of a concrete inverted siphon.

cause serious washouts that will damage the structure and the surrounding area. The higher the fill, the greater the potential damage from breaks or holes made by burrowing animals. The ditches can be lined to lessen this hazard and to reduce seepage. If an elevated ditch crosses a drainageway, a culvert is needed.

Road-Crossing Structures.--Culverts, inverted siphons, or bridges are used to carry water across roads. Culverts are used most often under farm roads because they are generally the least expensive. Corrugated metal, smooth metal, and concrete are used most commonly for culverts in farm ditches. The culverts should be long enough to maintain a roadway of adequate width and must have enough covering to protect the pipe from concentrated loads. Inverted siphons are particularly suited to crossings at which the water surface in the ditch is higher than the road.

Bridges can be used for road crossings over ditches regardless of the elevation of the water in the ditch. They can be built so there is little or no loss of head through the structure.

Grade-Control Structures

Some irrigation ditches are built with enough grade to produce erosive velocities. Such velocities scour the ditch and may cause the banks to slough. The eroded material is deposited downstream, thereby reducing

ditch capacity and increasing the maintenance needed. Some protective measures therefore must be used, such as drops and chutes to control grade and linings to protect the banks. But in some places it may be better to use a pipeline instead of a ditch.

Drops.--Drop spillways or pipe drops control ditch velocity by lowering the water abruptly from one level to a lower level. A drop spillway is a weir. Water flows through the weir opening in the headwalls, drops to a nearly level apron spilling basin or to a lower level, and then flows into the downstream section of the channel. For small drops, a simple apron usually is adequate. For higher drops or bigger streams, some type of energy dissipater must be provided. Different kinds of drop structures are shown in figure 3-28.

Large open drops are usually built of reinforced concrete. Reinforced concrete, concrete block, rock masonry, or rot-resistant lumber, such as redwood, cedar, fir, or creosoted pine, can be used for smaller structures. Prefabricated structures made of steel or aluminum are also available. Metal drops should be treated against corrosion. Special cement or alloys may be required if the chemical concentration in the soil is high enough to cause rapid deterioration.

A pipe drop is a section of pipe with a riser equal to the required drop. A fill must be built across the ditch to direct water through the pipe. Corrugated-metal pipe drops are commonly used and are available commercially. Smooth steel, precast concrete, or clay pipe can also be used. Pipe drops are especially suited to small ditches. The fill across the ditch can be widened by adding extra pipe to provide a road crossing if needed, which is an important feature. Pipe drops are more easily plugged by trash than weirs are. The earth fill should be inspected frequently to protect against damage by burrowing rodents.

Chutes.--Chutes are paved or lined, high-velocity, open channels. They can be used as short ditch sections on steep slopes or where drop structures would be so close together that a paved ditch is more practical. The paving or lining material for the chute must be able to withstand high-velocity flow. Chutes are usually built of concrete.

High velocity is a problem if it is necessary to divert some of the flow into farm ditches. If a chute empties into an earth ditch, some kind of spilling basin is needed to slow down and smooth out the flow to protect the ditch. Chutes are expensive and must be designed individually.

Distribution-Control Structures

Distribution-control structures are required for easy and accurate distribution of irrigation water to the various fields on a farm. Good water control permits efficient distribution and application and reduces labor requirements. Selecting the correct kind of water-control structure and locating it properly is an important part of planning a farm irrigation system.

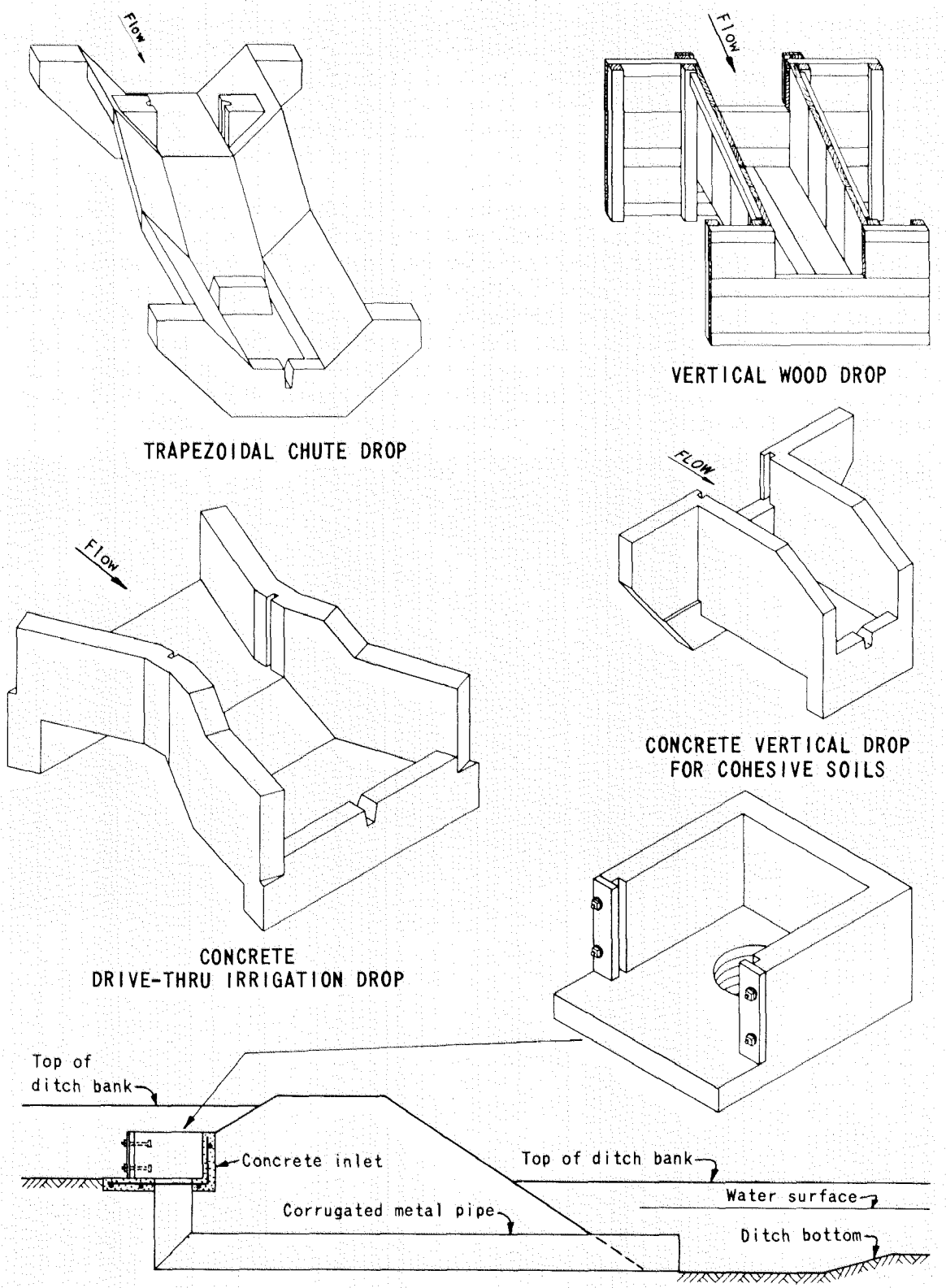
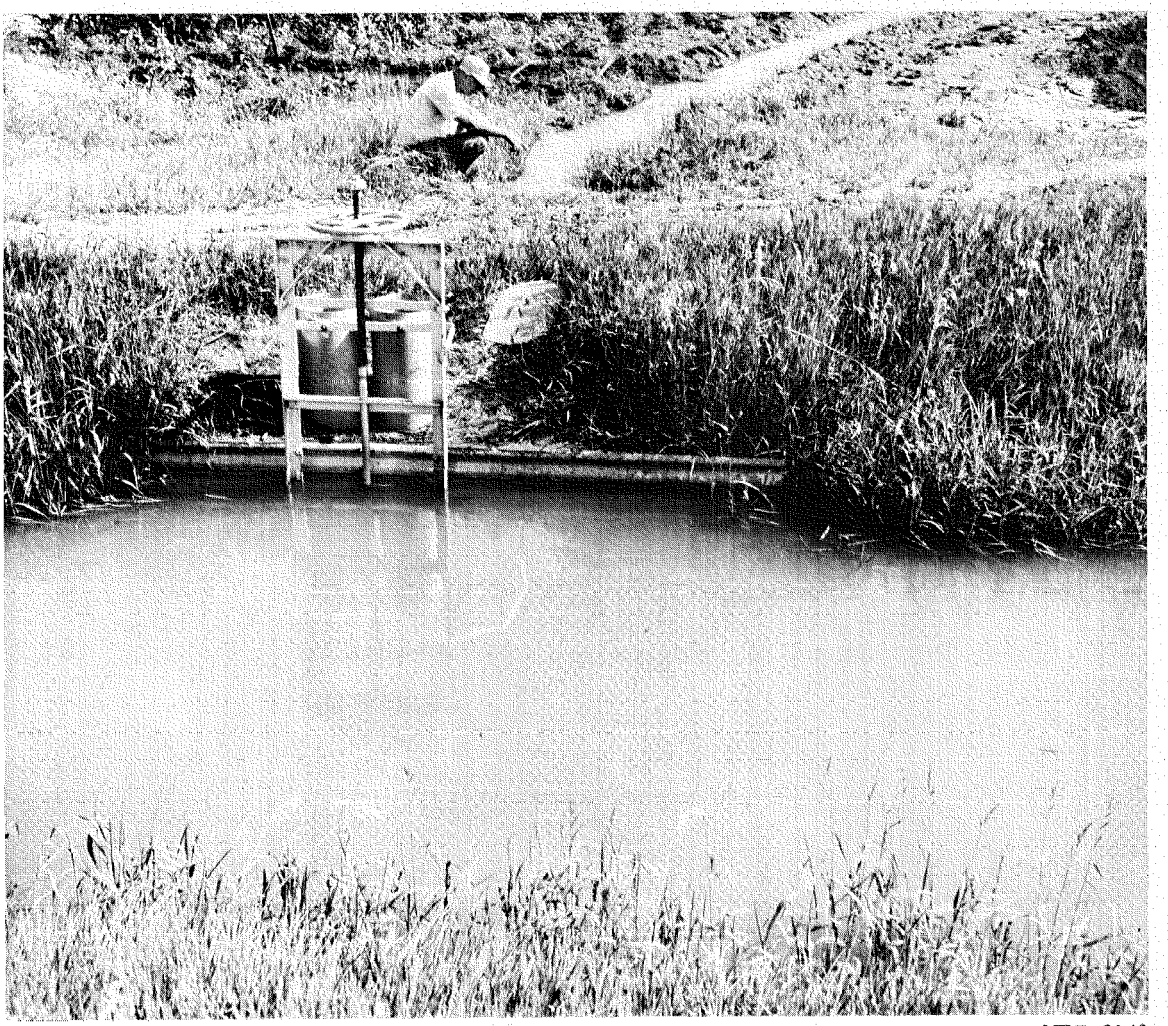


Figure 3-28.--Five drop structures.

Headgate.--Farm headgates are used to divert the required amount of irrigation water from the farm source of supply to the farm field ditches. Headgates may include a weir measuring device that determines flow into a field ditch (fig. 3-29). They may be culvert-type diversion structures equipped with a measuring well or submerged orifices with measuring gages.

Division Box.--Division boxes are used to divide or direct the flow of water between two or more ditches. Water enters the box through an opening on one side and flows out through openings on the other sides equipped with gates of a size to furnish the necessary flow to the field ditches. Division boxes are also used at pumps to control the flow of water from the pump outlet into one of two or more field ditches (figs. 3-30 and 3-31). Concrete or concrete block are the materials generally used for division boxes. Prefabricated metal panels that can be bolted together to form a box quickly and easily are also available.



NEB-2143

Figure 3-29.--Headgate equipped to measure water directly from an irrigation canal to a farm ditch.

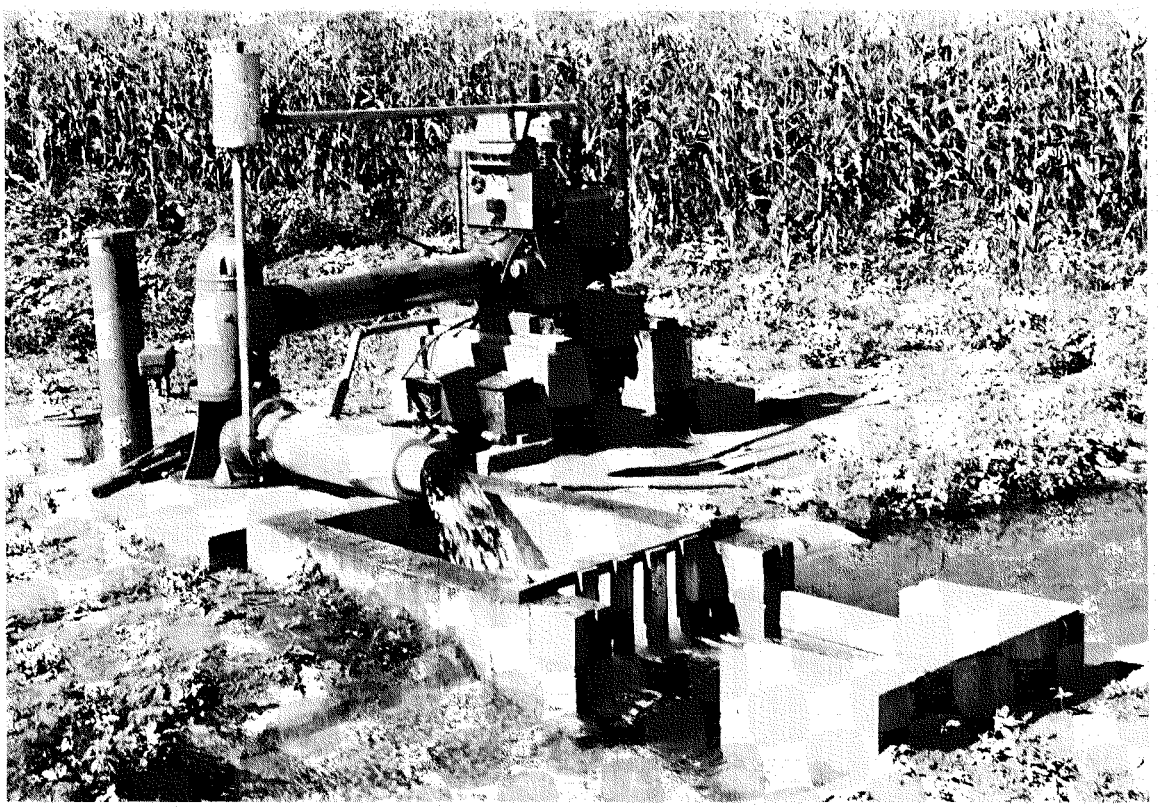


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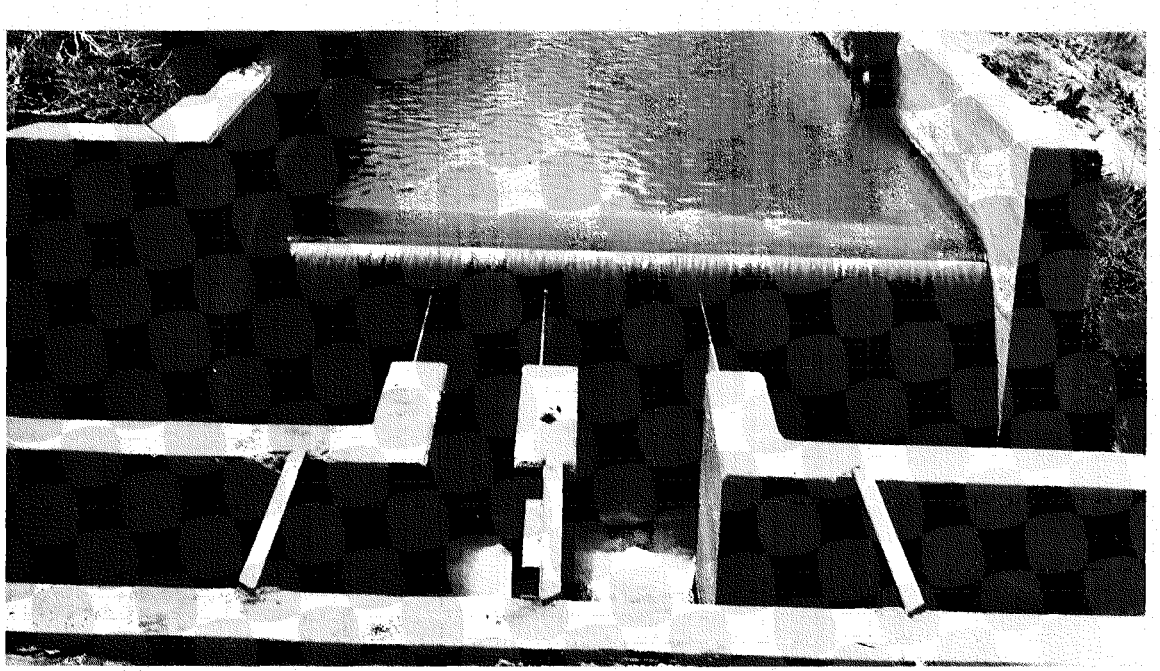
Figure 3-30.--Pump stilling basin and division box.



COLO-11178

Figure 3-31.--Division box with four chambers.

Checks.--Checks are structures placed in a ditch to form adjustable dams to control the elevation of the water surface upstream so that water can be diverted from the ditch. Checks can be permanent or portable. Different kinds of checks are shown in figures 3-32 through 3-39.

A permanent check is a headwall with a weir opening equipped with grooves for flash boards or with metal slide gates for adjusting the upstream elevation of the water surface. Boards can be used as stops. By changing the number or height of the boards, the upstream elevation can be controlled as well as the degree of overpour. If slide gates are used, the upstream elevation is controlled by raising the gate so that the excess water flows under the gate.

Permanent checks used in the more nearly permanent ditches generally are made of concrete, wood, or steel. Checks can also be combined with drops. Permanent overfall checks in unlined ditches should have an apron for the overflow to prevent scouring that might wash out the check.

Portable checks can be removed after they have served their purpose for irrigating a given area and reset downstream for irrigating another area. They are generally made of canvas, plastic, rubber, or metal. Metal checks are forced into the sides and bottom of a ditch, the others are dug in and then backfilled so that they do not wash out. Portable checks can also be used in concrete- or asphalt-lined ditches. Portable metal checks usually are laid on a slant in lined ditches and are held in place by the weight of the water.

Relifts.--Relifts are used to lift water by pumping from a ditch to a ditch at a higher elevation. A pump sump is built in the lower ditch where the pump is to be located. A pump discharge bay of concrete, concrete block, lumber, or metal is generally needed in the upper ditch to prevent damage from the pump discharge. Relifts are used if the farm water supply is not high enough to reach all areas of the farm by gravity flow.

Application-Control Structures

The amount and rate of flow of irrigation water applied to a field must be adjusted to the water-holding capacity and intake rate of the soils, thus saving both labor and water. Various kinds of structures are available for controlling and adjusting the flow of water from field head ditches to individual furrows, corrugations, border strips, contour ditches, and subirrigation ditches.

Turnouts.--Turnouts are boxes or orifice-type structures in the bank of a head ditch that provide and control the flow of water from the head ditch into border strips, contour levees, and contour ditches. They usually have some type of simple slide gate to regulate the flow. Wooden boxes and concrete or metal pipe are generally used for turnouts (figs. 3-40 through 3-47).

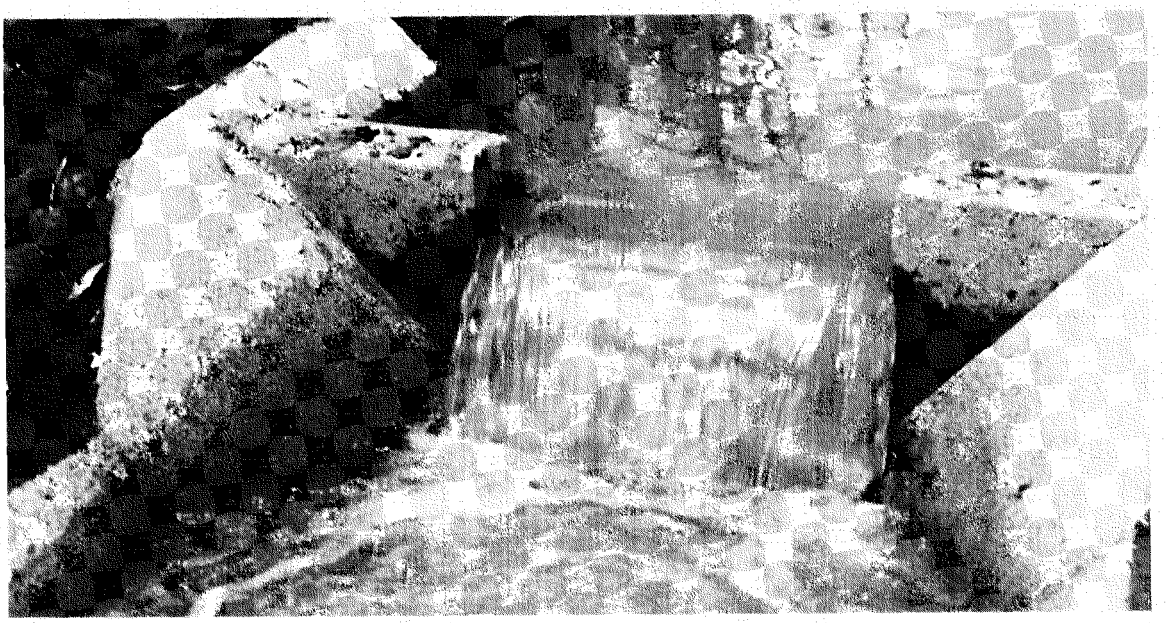


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Figure 3-32.--Combination drop and check.

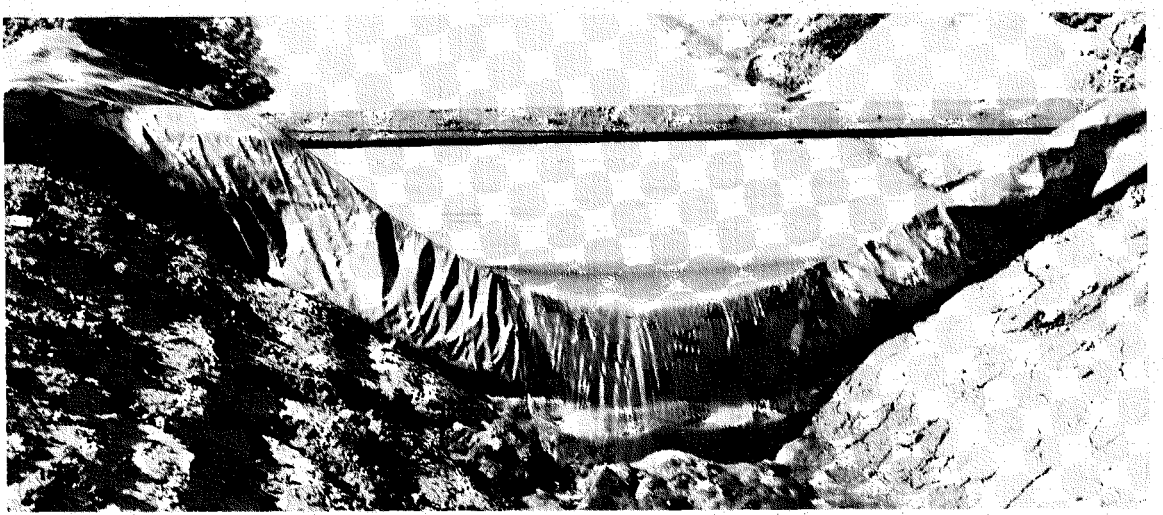

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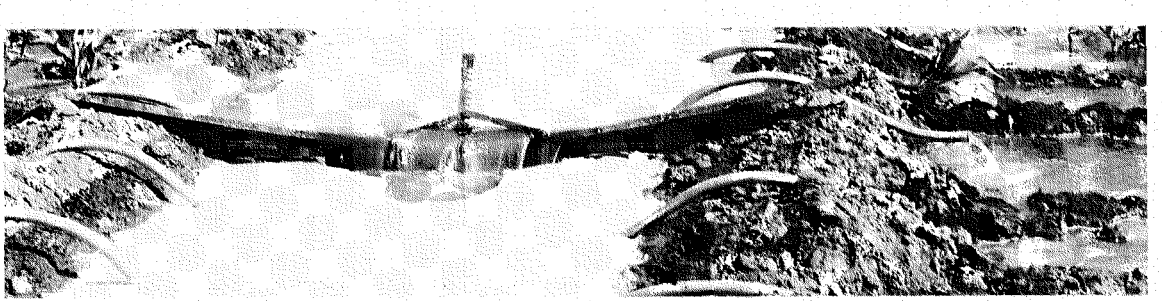
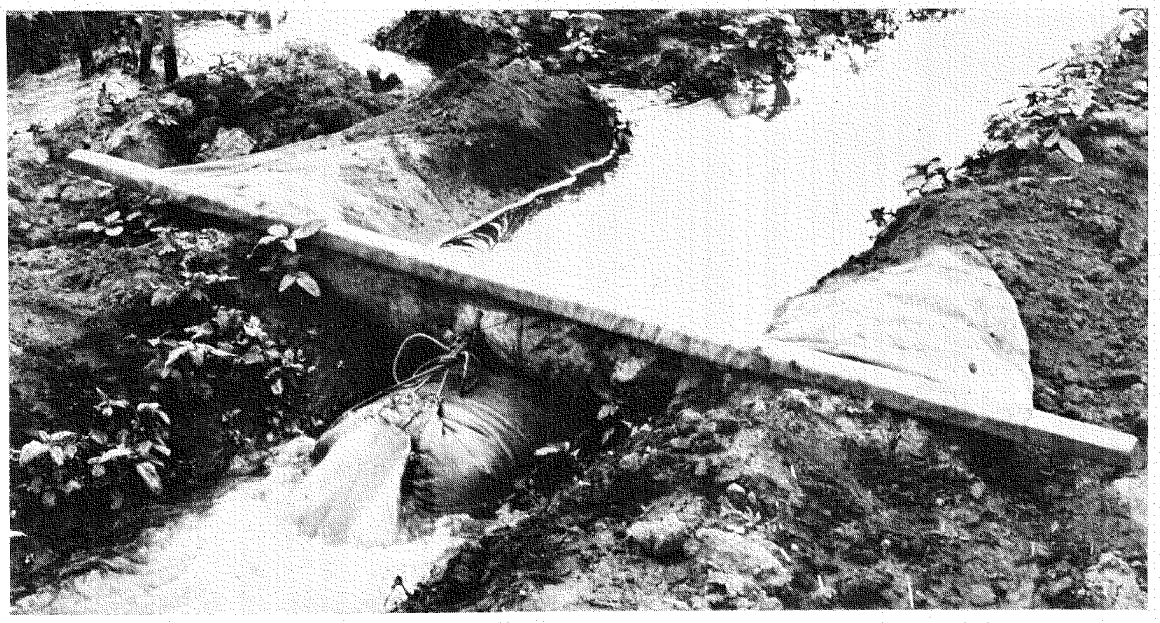
Figure 3-33.--Portable plastic check.



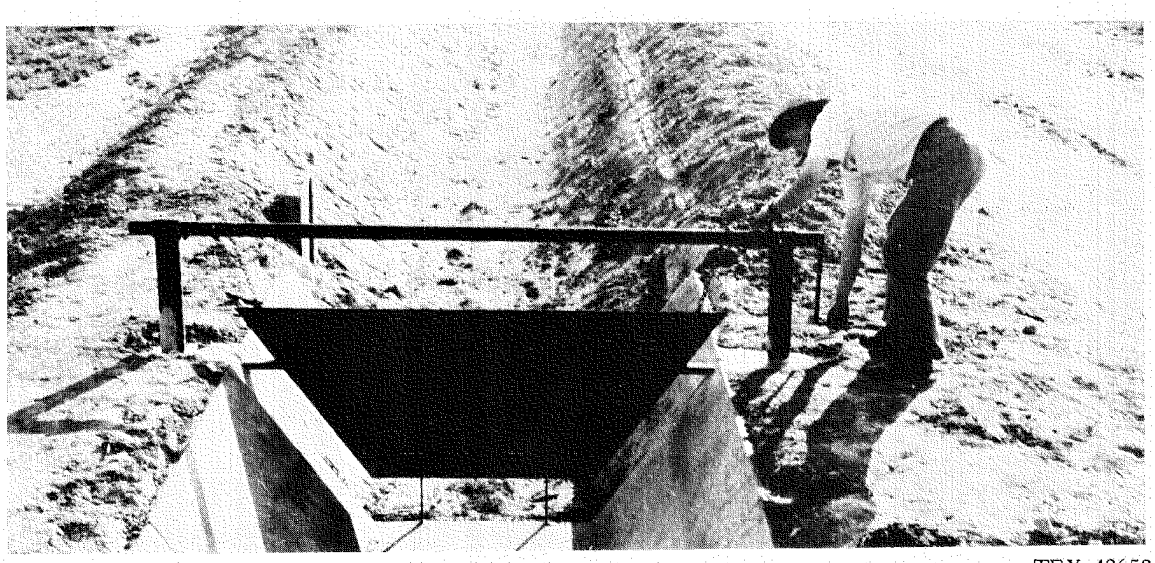
OKLA-11150

Figure 3-34.--Portable canvas check.



NEB-1617

Figure 3-35.--Canvas check with adjustable sack outlet.



TEX-42652

Figure 3-36.--Metal windless check.

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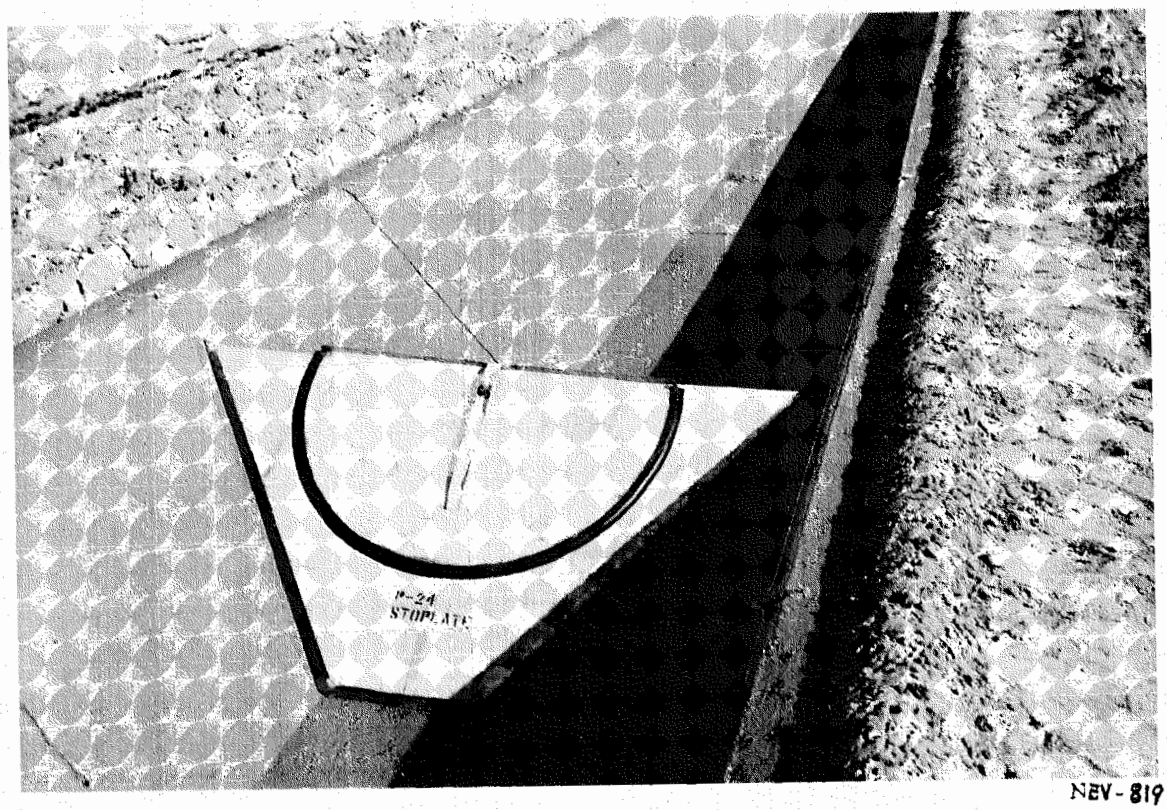
Figure 3-37.--Adjustable metal check in a lined ditch.

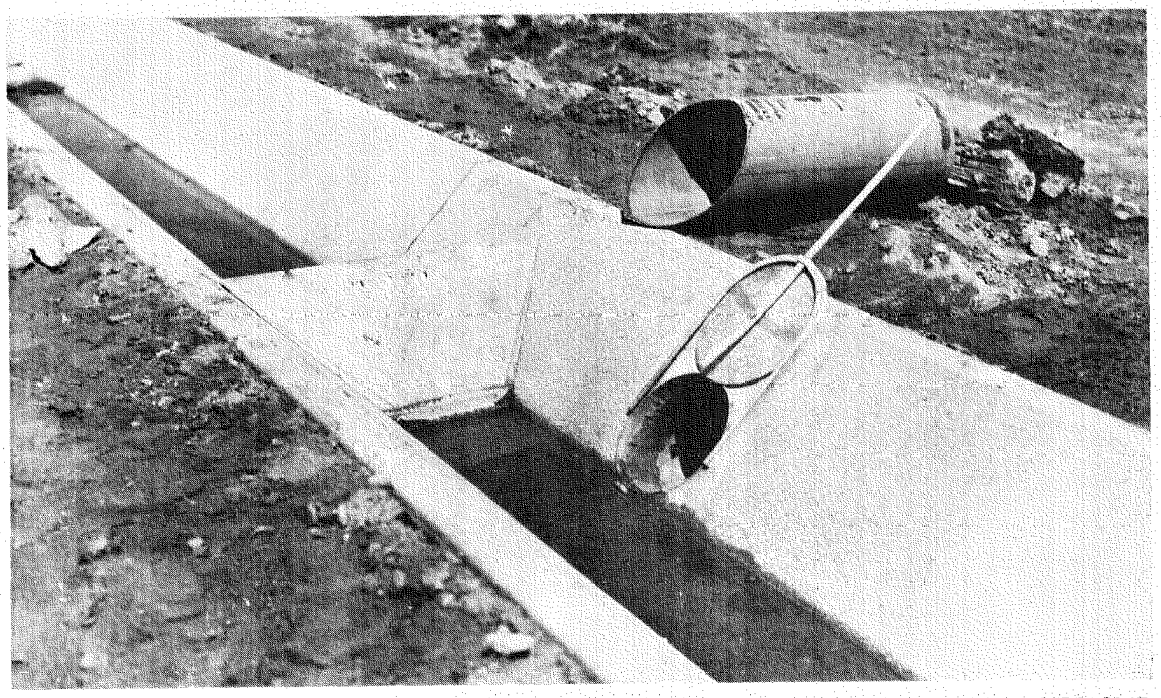
WYO-656

Figure 3-38.--Permanent concrete check.



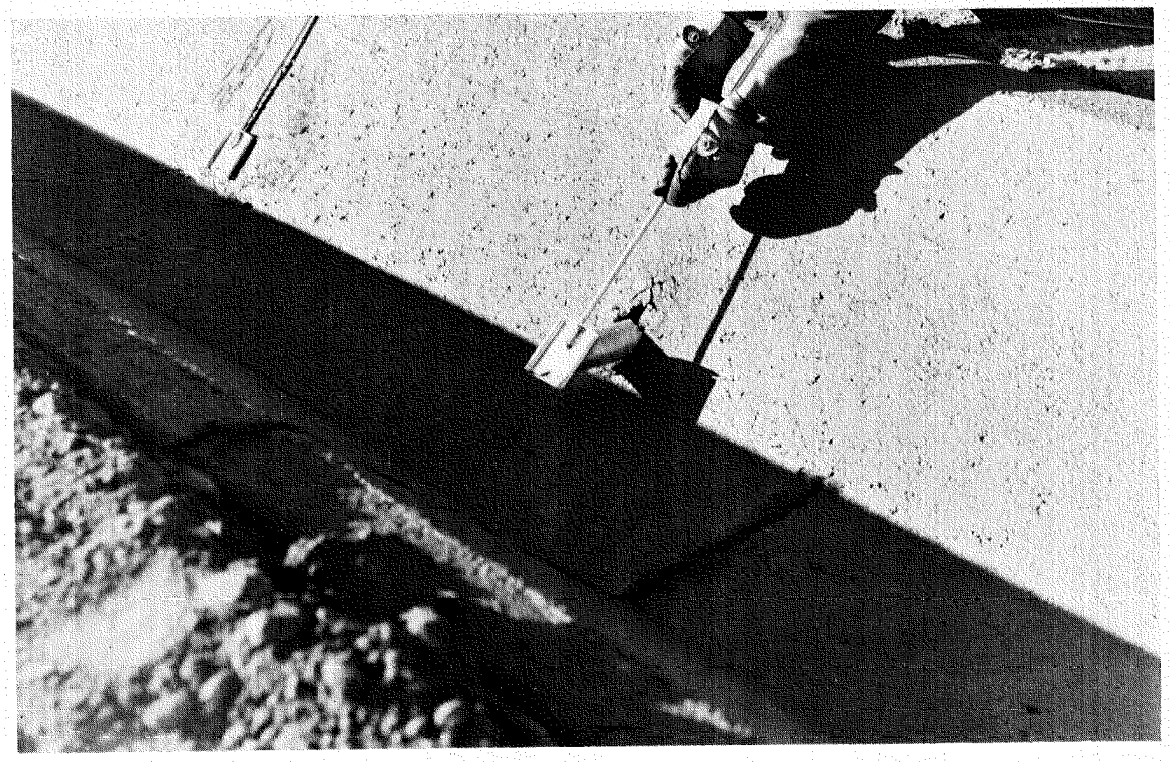
NEV-819

Figure 3-39.--Installing a metal check.



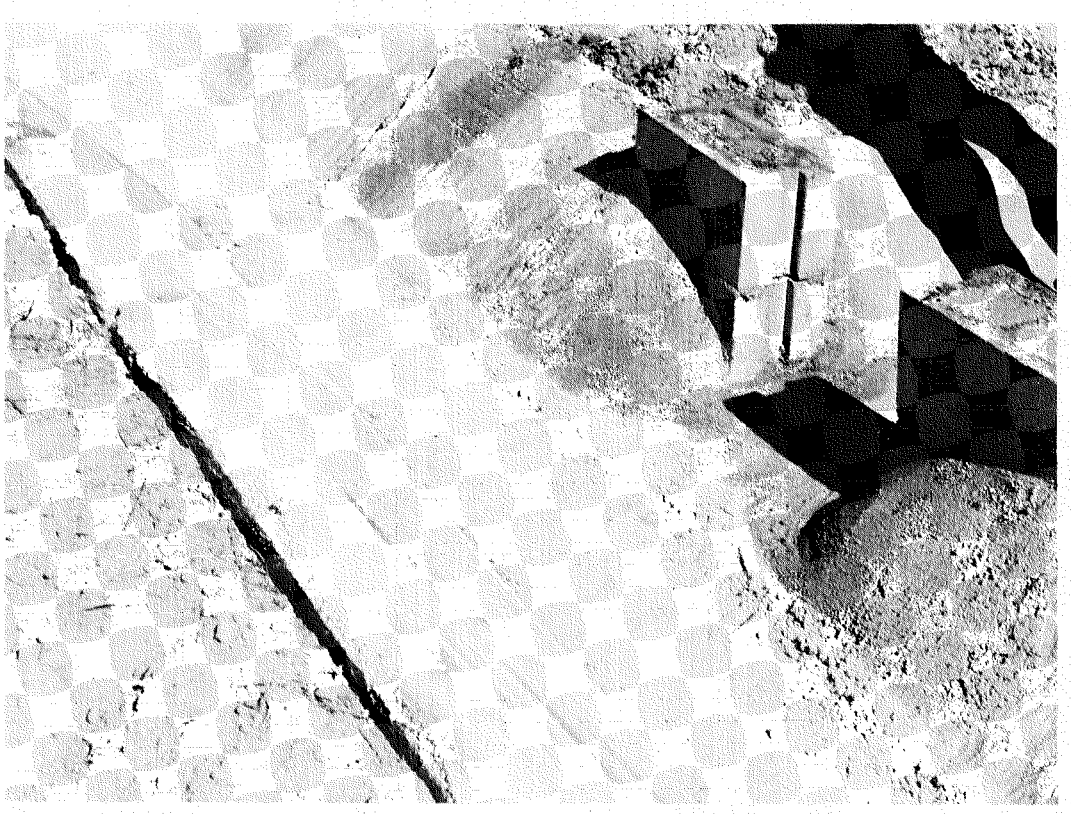
NEB-2147

Figure 3-40.--Metal-pipe turnout in a lined ditch.



COLO-11264

Figure 3-41.--Two-inch gate turnout.



WYO-10166

Figure 3-42.--Concrete-block turnout in a lined ditch.

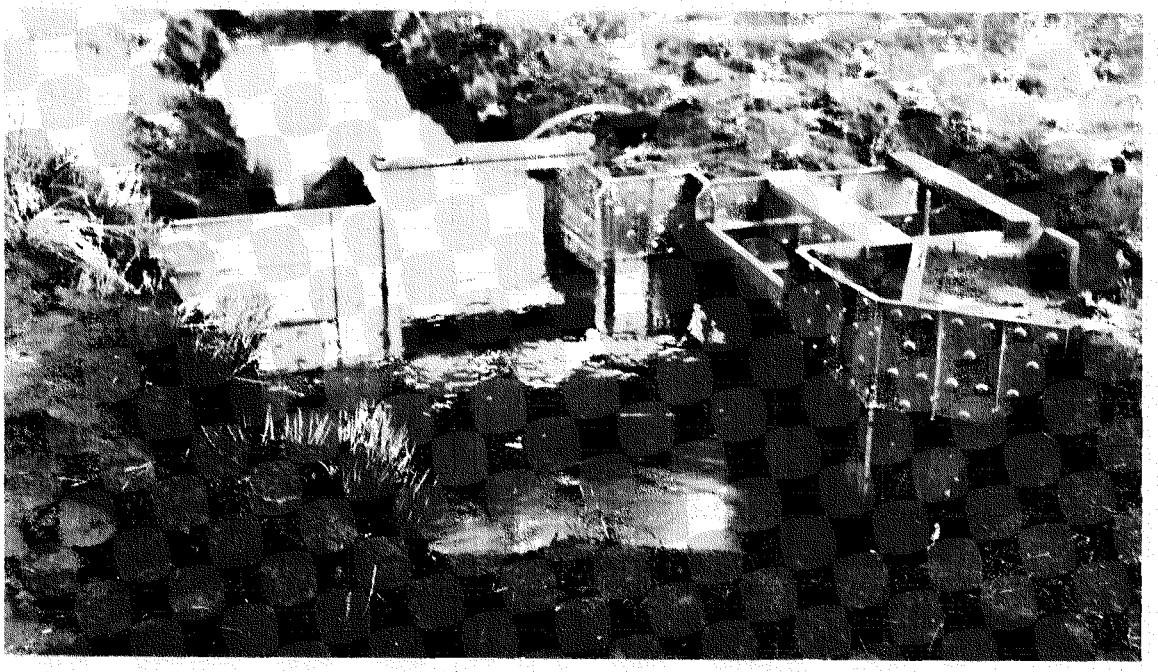


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Figure 3-43.--Metal turnout.

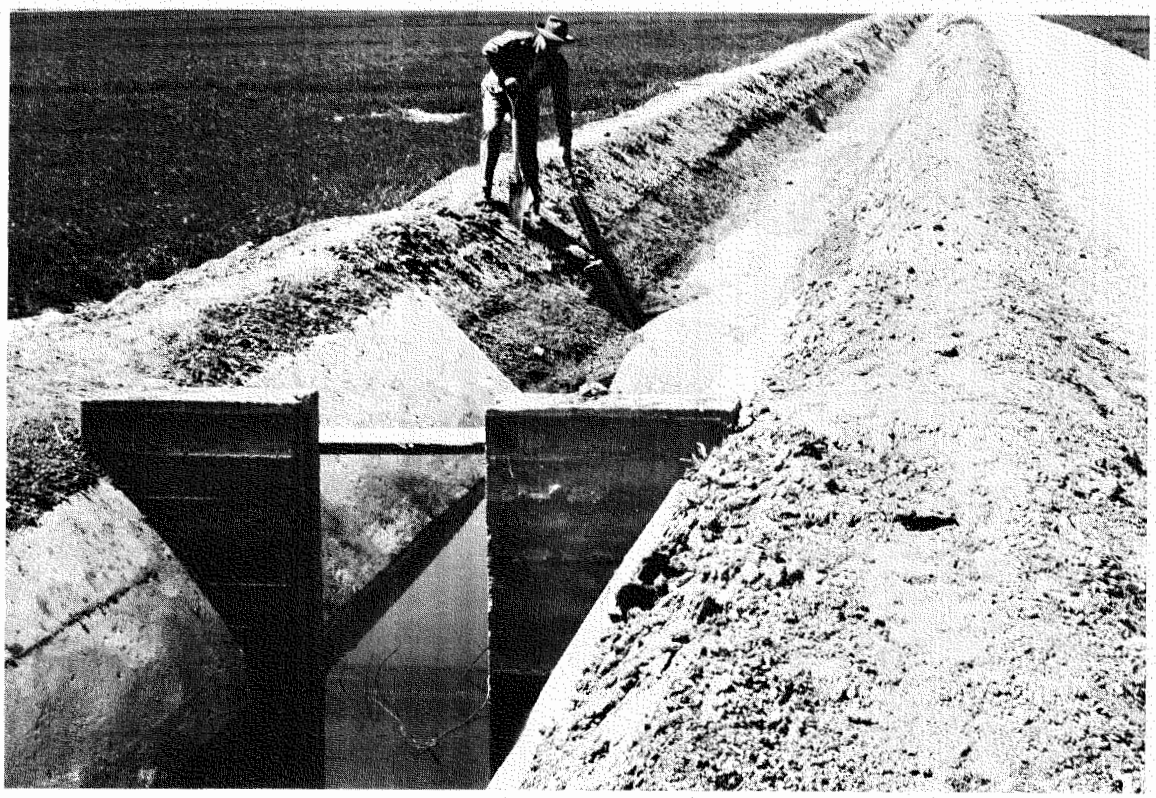

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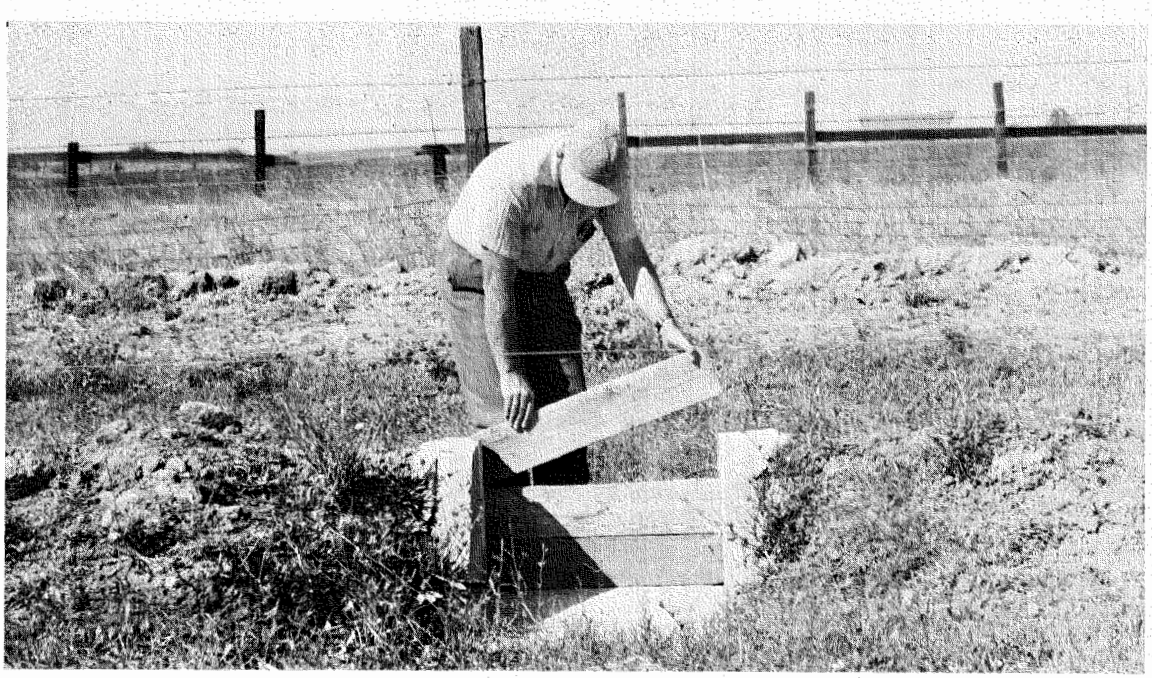
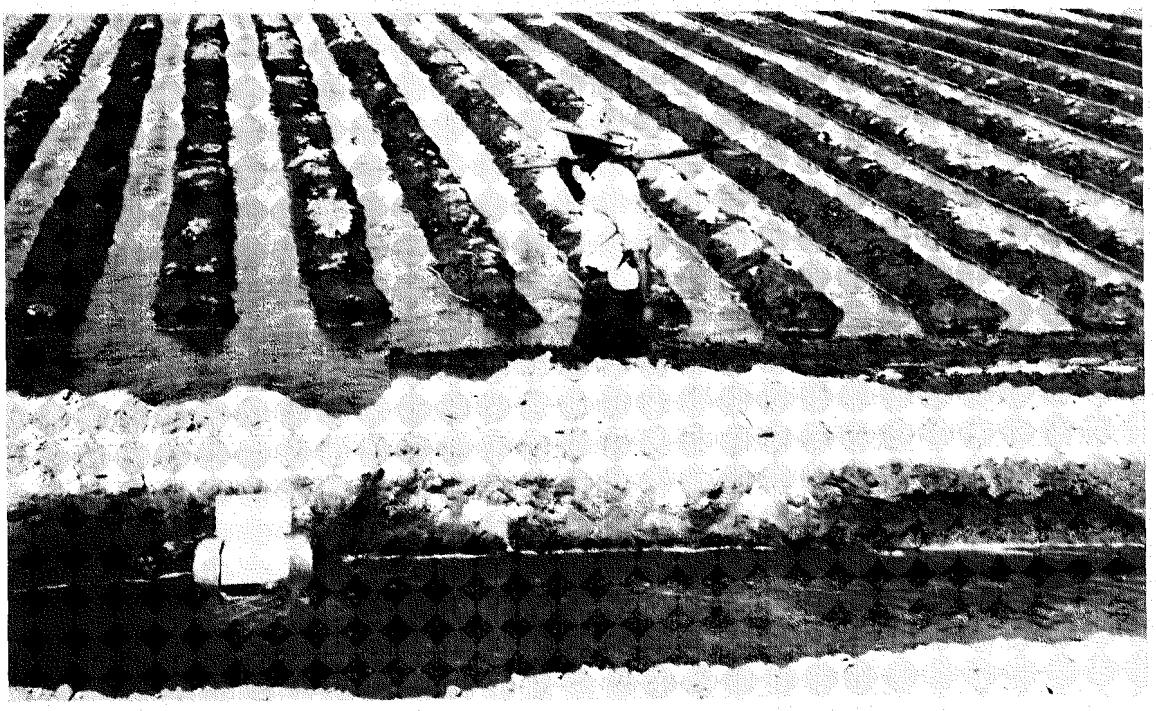
Figure 3-44.--Turnout boxes in background.



CAL-7344

Figure 3-45.--Concrete turnout with a flashboard gate.



TEX-42667

Figure 3-46.--Concrete-pipe turnout.

IDA-45359

Figure 3-47.--Installing a concrete-pipe turnout.

Concrete- or metal-pipe turnouts must be long enough to extend through the ditch bank. They should be equipped with an antiseep collar and a slide gate. In lined ditches turnouts should be located carefully and be installed at the time the ditch is lined.

Siphon Tubes.--Siphon tubes are small curved pipes that deliver water over the head-ditch bank to corrugations, furrows, and borders (figs. 3-48 and 3-49). Water flows through the tube by the force of atmospheric pressure on the water in the ditch. One end of the tube is placed in the ditch and the other end outside the ditch on the ground surface, which must be lower than the water level in the ditch. The tube must be completely filled for flow to start.

Plastic, metal, or rubber siphon tubes are available commercially. They come in many sizes, having a flow capacity from as little as 1 gallon per minute to more than 1,000 gallons per minute. Capacity varies with tube size and the head on the siphon. Often two or more small tubes are used for each furrow until the water reaches the lower end, then one (or more) is removed to cut back the stream. Flow through siphon tubes can be regulated by controlling the orifice at the outlet or by changing the head.

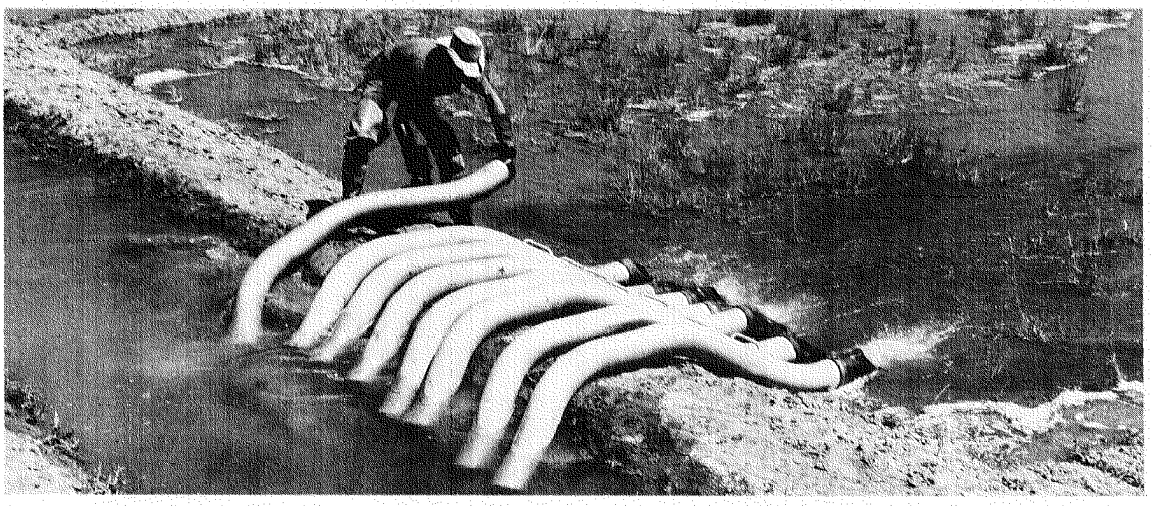
Large siphon tubes, 4 to 8 inches in diameter and 5 to 12 feet long, can be used in place of turnouts. Siphon tubes are used because they can be moved, thus reducing cost of material, but the cost of labor for moving and priming is increased. Another advantage is that ditches are open for cleaning. Siphon tubes are particularly suited to taking water out of a raised ditch. One great difficulty in using large tubes is priming. It is possible to obtain large siphons with adjustable gates on the discharge end, which can be primed by pumping air out of the tubes with a pump on the valve at the top (fig. 3-50).

Gated Pipe.--Gated pipe is portable metal pipe, usually aluminum, with a number of small gates along one side through which water can be run into corrugations, furrows, or borders (figs. 3-51 and 3-52). The pipe can be furnished with gates spaced to match furrow spacing, and the gates can be adjusted to control flow into the furrows. The gates provide positive control and are particularly good if cutback streams are required. The pipe is made in light-weight sections, usually 4 to 12 inches in diameter, that are coupled together easily.

Gated pipe can be used in place of a head ditch at the top of a field or it can be used in conjunction with the head ditch. It is well suited to use in place of an intermediate head ditch on fields too long to be irrigated in one length of run. This permits cultivation through several lengths of run since the pipe can be uncoupled and laid parallel to the rows or be removed from the field during cultivation. Gated pipe is used especially to deliver water to benches and cross-slope or contour furrows. It also provides good control of water on slopes too steep for effective distribution from an open ditch.

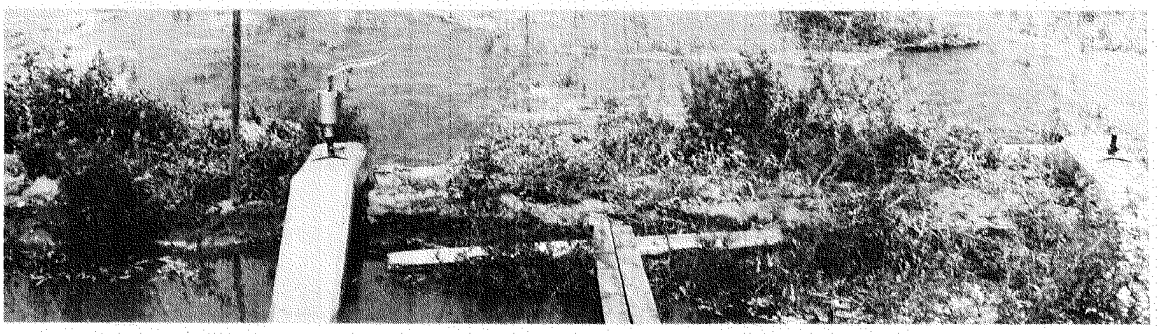
TEX-49881

Figure 3-48.--Two-inch siphon tubes irrigating furrows.



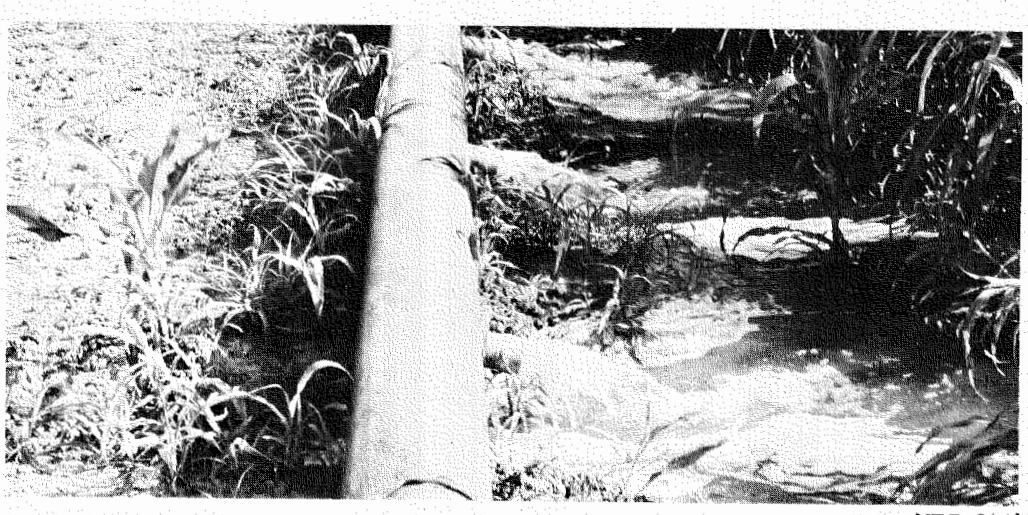
COLO-11149

Figure 3-49.--Eight-inch siphon tubes irrigating a border.



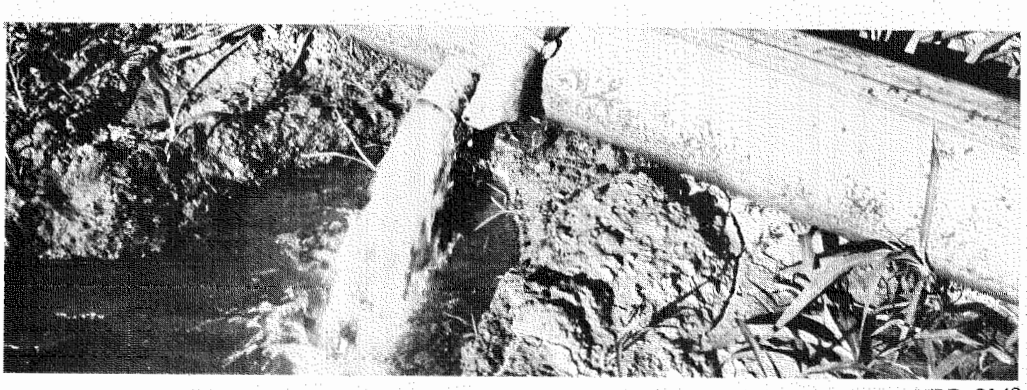
Bn-29651

Figure 3-50.--Large metal siphon and pump for priming.



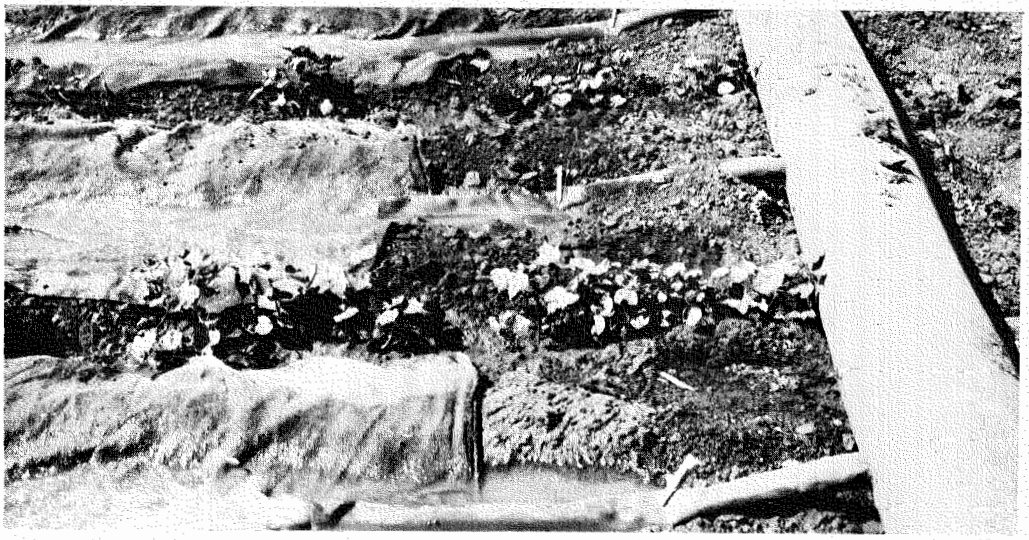
NEB-2148

Figure 3-51.--Gated pipe for furrow irrigation of corn.



NEB-2149

Figure 3-52.--Closeup of gate in pipe.



OKLA-11898

Figure 3-53.--Flexible gated pipe; sacks prevent erosion and clothespins regulate flow.

Flexible Gated Pipe.--Flexible gated pipe, sometimes known as surface hose or lay-flat tubing, can be made of plastic, rubber, or canvas with outlet tubes spaced according to the furrow spacing (fig. 3-53). There are various means of adjusting flow through the outlet tubes, for example, adjustable clamps. Flexible pipe or hose can be rolled up for easy moving and storage and can be used in the same places as gated metal pipe. Initial cost is less than that for gated metal pipe. Plastic and canvas pipes have the disadvantage of short life and must be handled carefully. Rubber pipe has a longer life but is heavy.

Spiles.--Spiles are pipes, 1 to 4 inches in diameter, used to distribute water from a ditch into corrugations or furrows. They are set permanently in the bank of the head ditch and must be long enough to extend through the bank. They are used at places where the head ditch is nearly flat. The water elevation in each ditch section can then be controlled by a check. It should be high enough above the center of the spile opening to deliver the maximum nonerosive stream until the water reaches the end of the run. Then the water can be lowered to a point that delivers the cutback stream through the spiles.

Pipelines

Irrigation pipelines are a means of conveying water through closed conduits. Since pipelines are costly, careful planning is required for location, capacity requirement, selecting the best material, and good construction practices. Irrigation pipelines can be used for the same purposes or in place of open channels.

Pipelines can be either on the surface or underground. Portable surface pipe has an advantage over underground pipe in that it can be moved and used in more than one location, but it has a disadvantage in the labor required to move it. Underground lines are plain concrete, reinforced concrete, asbestos-cement, steel, wrapped aluminum, fiber, or plastic pipe (fig. 3-54). Surface pipe is made of aluminum, steel, rubber, plastic or canvas. The choice of material depends on the conditions under which the pipe is to be used, cost, and the farmer's personal preference.

Pipe conduits can be used in most places. They are particularly suited to areas where seepage losses are high. Pipe can be used to advantage in places difficult to excavate and to carry water down steep slopes. Pipelines are also good in areas where water supply is limited and losses must be kept to a minimum. Pipelines almost eliminate losses from evaporation and seepage. Weed control and farming operations are easier, and less tillable land is taken up. Maintenance work in general is less than that for open ditches, and water control is easier.

Cost is probably the main limiting factor in using pipe to carry irrigation water. Even though the initial installation cost is higher than that for comparable open-ditch systems, the overall annual cost often is less.

Two general kinds of pipeline are used--low pressure and high pressure. Low-pressure pipelines are open to the atmosphere and are usually used with operating heads of less than 20 pounds per square inch. High-pressure pipelines are closed to the atmosphere and are used where operating heads of more than 20 psi are required. Valves are used in lieu of open vents and stands.

Low-Pressure Pipelines

Low-pressure pipelines are used primarily with surface irrigation methods. They can be permanent, semiportable, or portable. Permanent farm systems usually consist of buried supply and distribution lines. In semiportable systems buried pipe is used for field supply lines, and some kind of quick-coupling metal pipe or flexible pipe is laid on the ground surface to distribute the water. A fully portable system uses metal or flexible surface pipe for both field supply and distribution.

Concrete generally is used for low-pressure buried lines, but steel, wrapped aluminum, fiber, asbestos-cement, or plastic pipe can be used. Concrete pipelines are either precast (fig. 3-55) or cast in place (figs. 3-56 and 3-57). Concrete pipe is made with tongue and grooved joints, which are sealed with rubber gaskets or filled with cement mortar.

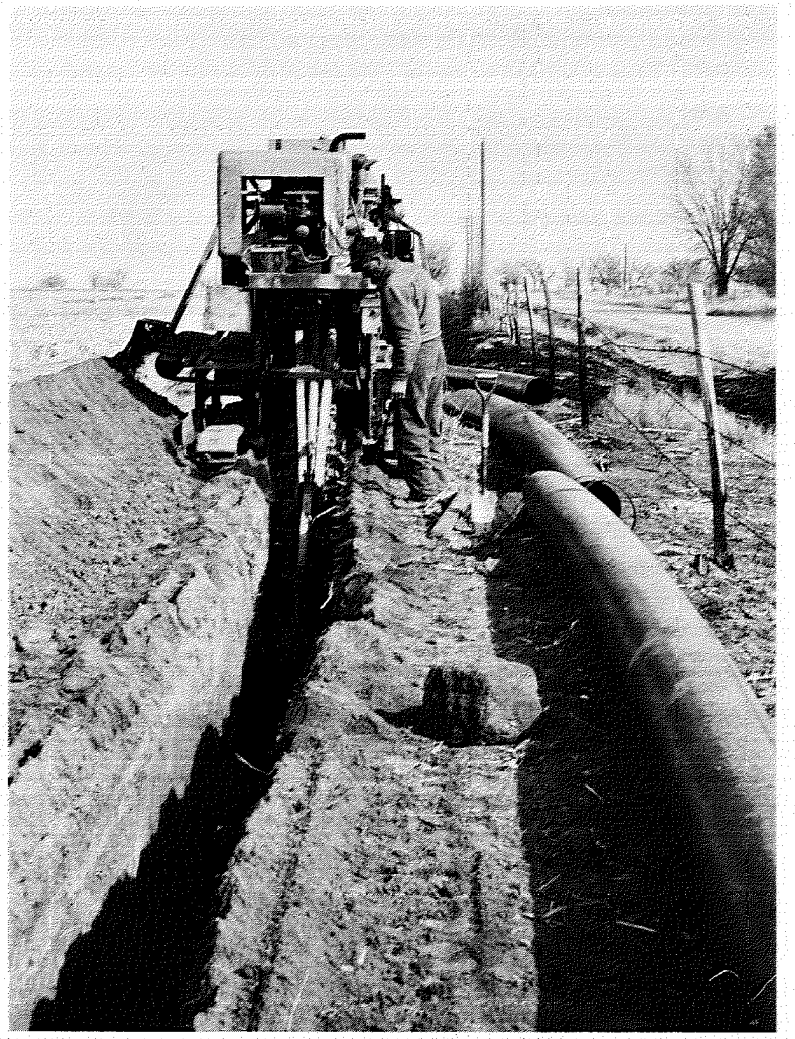
It is very important that a pipeline be large enough to convey the flow needed in different fields under present and future conditions. It must be large enough to supply the water required during the period of peak crop use even though this full capacity may be needed in only a small part of the total irrigating season.

Specialized structures are needed on pipelines to control water and to protect them against damage. Pipelines on sloping land may develop excessive pressure heads that must be controlled by standpipes or regulating valves. Lines fed directly from pumps also must have structures for controlling the maximum pressure automatically.

High-Pressure Pipelines

High-pressure pipelines generally are used to convey water for sprinkler irrigation. Since sprinklers usually require a pressure of 40 pounds per square inch or more for efficient water distribution, the pipeline must be designed as a high-pressure system to withstand this pressure. The supply line or sprinkler main line may be a permanent buried line or a portable metal surface pipeline. Buried lines cost more to install, but their maintenance and operating costs are lower than those for surface pipe. Buried lines do not interfere with farming operations and are less likely to be damaged by farm machinery and vehicles.

A buried main line may extend from the water source to individual fields, and surface pipe is used for the field main and laterals. This permits moving the field main and laterals to other fields. Or a buried main line can extend into the fields to be the field main and have risers and valves at the location of each lateral line.

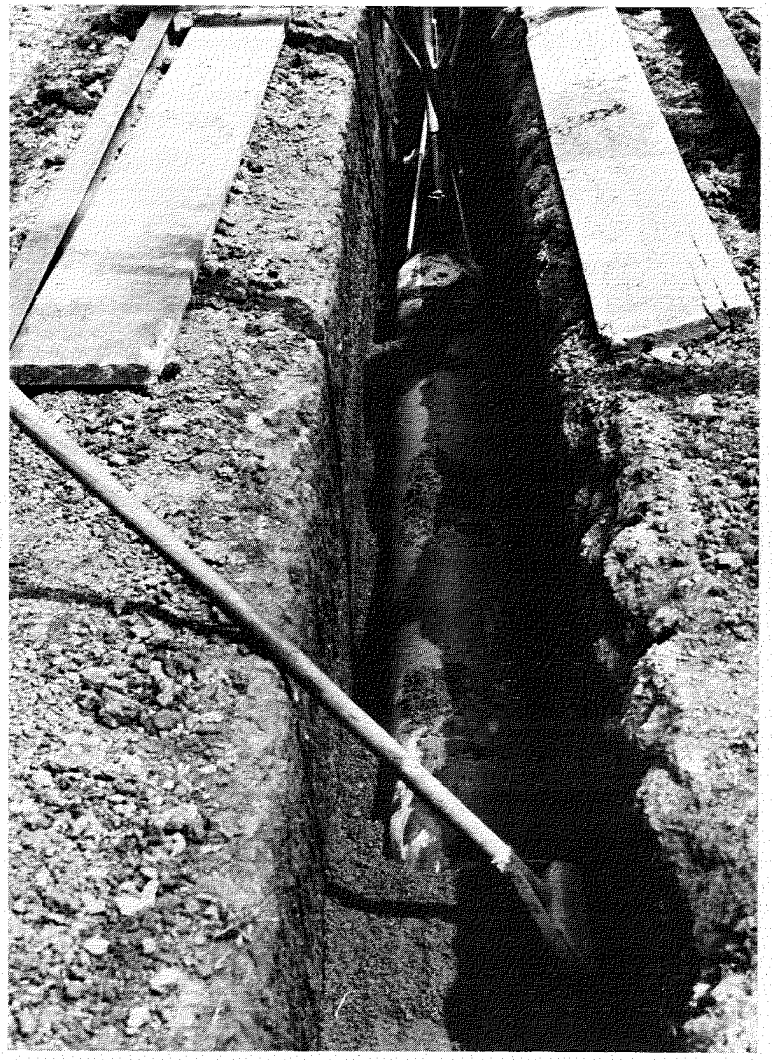


COLO-11187

Figure 3-54.--Installing plastic pipeline.

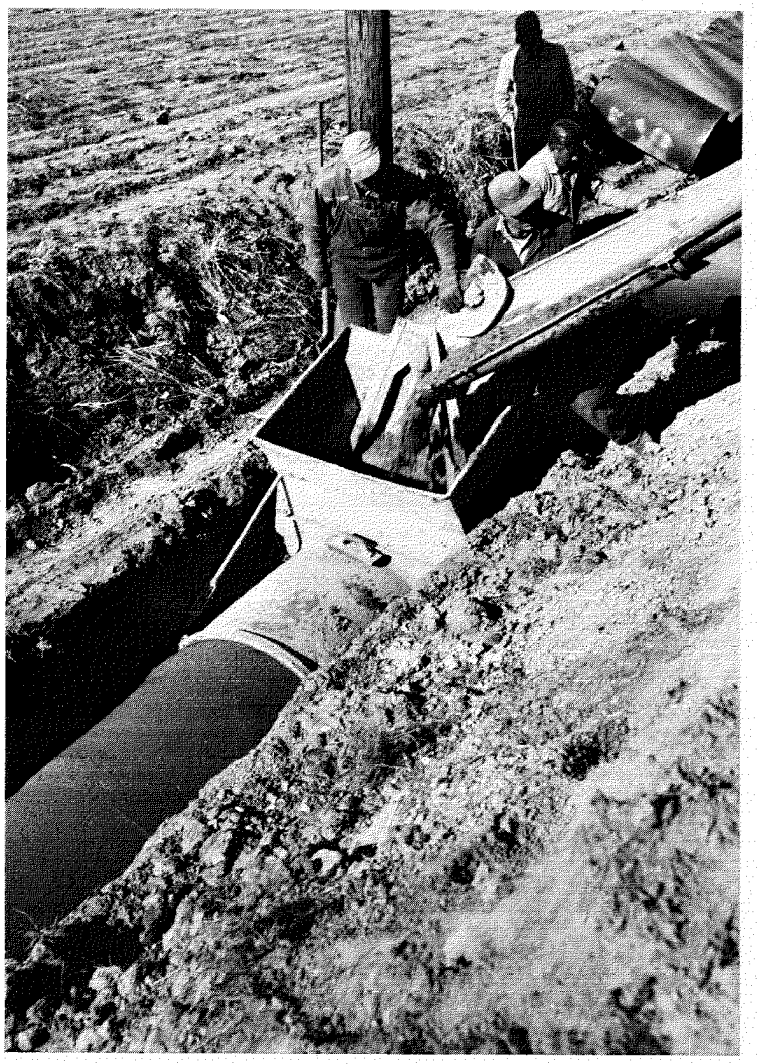
COLO-11172

Figure 3-55.--Installing 15-inch concrete irrigation pipe.



NEB-2151

Figure 3-56.--Removing inside form from concrete pipeline cast in place.



COLO-11263

Figure 3-57.--Pouring concrete pipeline using sheet-metal slip form.

A buried main line is either metal, asbestos-cement, or plastic pipe. Portable surface lines are aluminum pipe in 20-, 30-, or 40-foot lengths with quick couplers, plastic pipe, or hose. If the water is from an open source where debris can collect, trash screens should be installed at the pump inlet. The screens should be fine enough to remove weed seeds and other small particles that may clog sprinkler nozzles. Chapter 11 contains information on selecting and designing sprinkler systems.

Inlet Structures

An inlet structure is often needed to prevent damage from excessive pressure, to develop the full flow capacity of a pipeline, and to keep trash from entering the pipe. The kind of structure depends on the water source since water enters by gravity flow from a ditch or is pumped into a line from a stream or well.

Pump Stands.--A pump stand is a vertical pipe extending above ground from a buried pipeline (fig. 3-58). It carries flow from the pump into the pipe system and must be large enough to let the air entrained by the high-velocity stream escape.

The stand must be high enough to prevent overflow at the usual operating pressure yet permit overflow at excessive pressure. High pump stands can be capped and vented with a pipe of small diameter (fig. 3-59). To prevent damage from vibration, the pump should be connected to the stand by a flexible coupling. Pump stands are usually used for low-pressure pipelines.

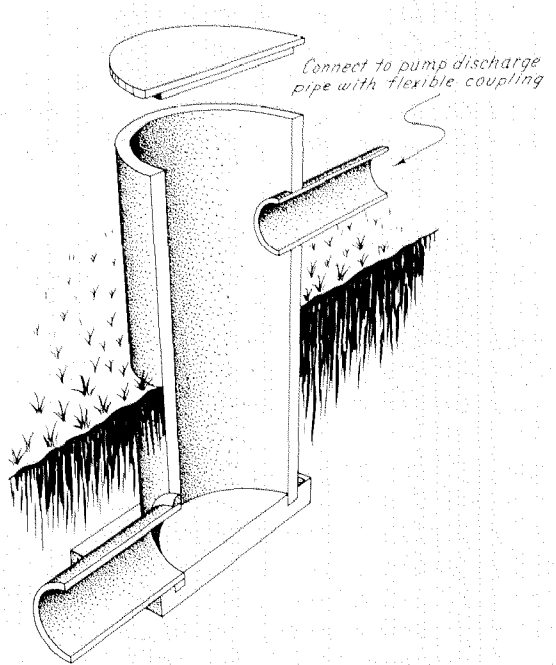
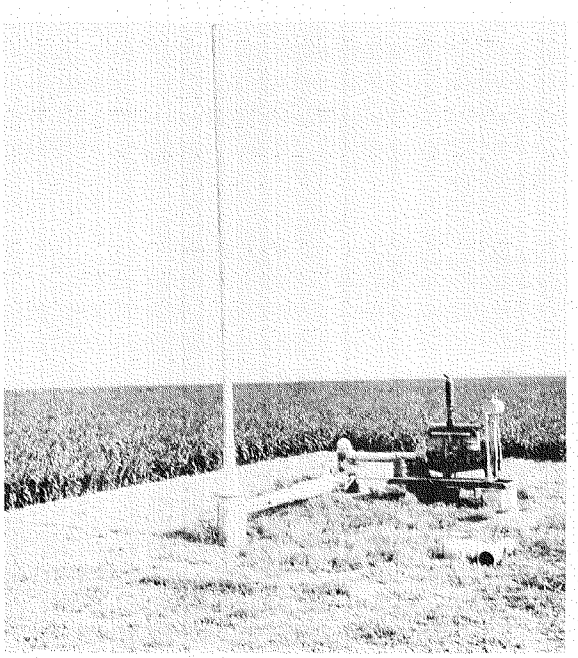


Figure 3-58.--Low-head open stand for concrete pipe.



NEB-2150

Figure 3-59.--Capped high-head steel stand.

Gravity Inlets.--For pipelines into which water flows by gravity from an open ditch, a gravity-inlet structure (fig. 3-60) that may include a sand trap, debris screen, or trash rack is needed to develop full pipe flow and keep trash out. The top should be covered to keep trash from blowing in and to prevent accidents.

Sand Traps.--A sand trap is a settling basin used to remove sand or silt carried in irrigation water. It can be built into the pump stand or gravity inlet by setting the bottom of the stand some distance below the bottom of the pipeline (fig. 3-61). The stand should be large enough to keep water velocity low and to permit cleaning.

Debris Screens.--Debris screens are used to remove trash, weed seeds, and other debris carried in irrigation water from open ditches, rivers, or lakes. This is especially important if sprinklers are used. If water is pumped into a pipeline from an open source, the end of the suction pipe can be fitted with a fine screen. Water entering by gravity flow should fall through a fine screen, which must be cleaned frequently. A horizontal self-cleaning screen can be installed if the water source is high enough to provide a drop of 1 foot or more at the pipe inlet (figs. 3-62 and 3-63). The falling water washes the trash to one side or completely off the screen.

Vents

Vents to relieve pressure and release air are used at all high points of a pipeline, at points where its slope sharply increases in the direction of flow, at sharp turns, at the end, and directly below any structure that entrains air in the flowing water. All vents must extend above the hydraulic grade line to prevent overflow when the line is operating normally. By allowing air to escape, vents permit a pipeline to carry more water, relieve surges and prevent damage to the line when gates or valves are opened or closed, and keep the line from collapsing when it is drained.

Straight Vents.--A straight vent is a pipe extending straight up from a buried pipeline. The diameter of the vent is the same as the diameter of the pipeline. Generally a straight vent is placed on top a hole cut in the line after the line is laid. The maximum height must not exceed the safe working head of the pipeline plus freeboard. An anchor should be cast around the pipe under the stand to maintain alinement.

Capped Vents.--A capped vent differs from a straight vent in that at or near the ground surface it is capped over and a smaller pipe extends through the cap to the necessary height, generally 2 feet above the maximum hydraulic gradient. The area of the small pipe should not be less than one-sixtieth of the area of the main pipe and the diameter should never be less than 2 inches. The cap should have a minimum height of two diameters above the crown of the pipeline. The smaller pipe is generally made of steel, sheet metal, or asbestos cement. Capped vents can be used in place of straight vents but commonly are used if

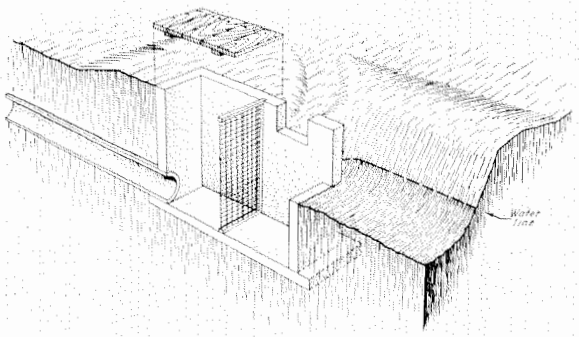


Figure 3-60.--Gravity inlet for buried low-pressure pipeline.

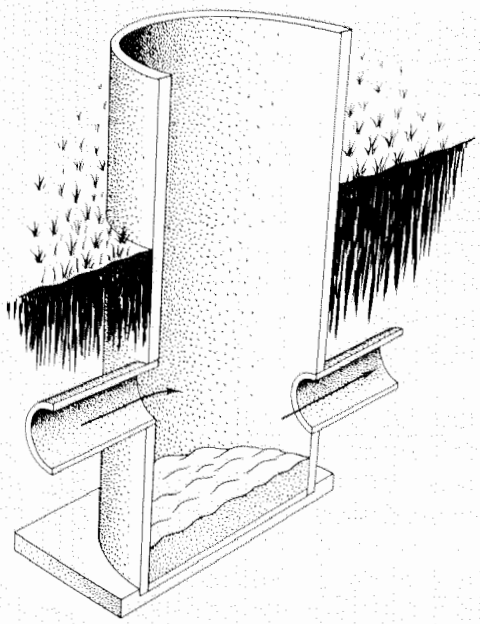


Figure 3-61.--Typical concrete-pipe sand trap.

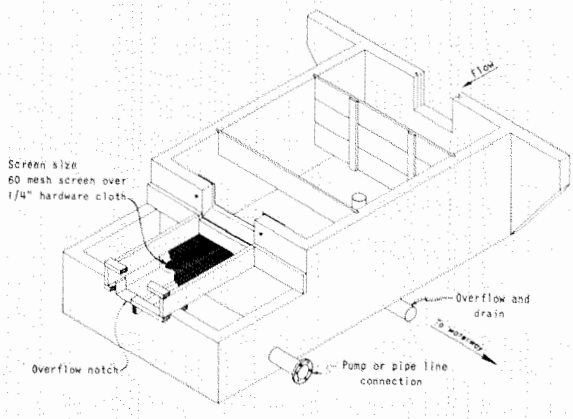


Figure 3-62.--Typical trash screen.

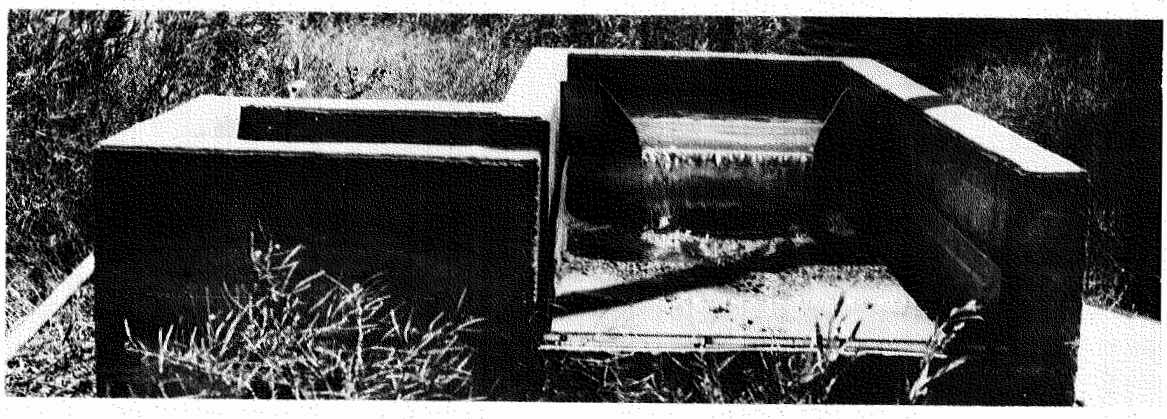


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Figure 3-63.--Desilting box and trash screen.

the hydraulic gradient is more than 8 feet above ground surface (figs. 3-64 and 3-65).

Air-Release Valve Vents.--These vents are capped vents that have an air-release valve in the smaller pipe at some convenient height above the ground. They are used in places where otherwise extremely high vent pipes would be required (fig. 3-66). When air enters the valve, a floating ball drops, opening the valve until the water rises again. The valve permits air to escape or enter but does not allow water to pass. If the valve sticks, a gate valve can be placed immediately below the release valve for use until repairs can be made.

Control Structures

Different control structures are used on irrigation pipelines to regulate the flow into branching lines, to remove entrained air, and to prevent momentary high pressures from damaging the pipeline.

Gate Stands.--Gate stands are similar to other types of stands but must be large enough to accommodate the gates to be used and to permit access for maintenance and repairs. They are used to control flow into laterals or to increase pressure upstream. The increase in pressure may be needed to force water from hydrants upstream. If laterals take off at the stand, the gates can be opened or closed to divert water as desired (fig. 3-67). Gate stands also prevent excessive pressure and act as air vents and surge chambers.

A gate stand may be concrete pipe or a concrete box, and a box stand is an excellent structure in which to install gates. Gates are usually set on the outlets from the stand so that water pressure in the stand closes the gates rather than holding them open.

It is possible to substitute line gates in each lateral line for the gates inside a stand. This is usually done if high stands are required. Line gates can be operated from the ground instead of from the top of the stand. They are not desirable if the structure must also serve as a sand trap.

Overflow Stands.--Overflow stands are generally two concrete pipe stands joined together--one at the pipeline elevation in which a gate is installed and the other at the elevation of the overpour lip. The upstream stand must be large enough to accommodate the gates to be used and to permit access for maintenance and repairs. Overflow stands (figs. 3-68 and 3-69) serve as both checks and drop structures in addition to the usual functions of a stand. They are not needed on flat areas or on very slight slopes but are used in areas where slopes are so great that excessive pressure can be developed downstream.

As checks, they regulate pressure to maintain constant upstream flow from hydrants or into laterals. As drop structures, they cause a drop on the hydraulic gradient, thus limiting pipeline pressure. The gate valve is open if upstream pressure is not required. If diversion or

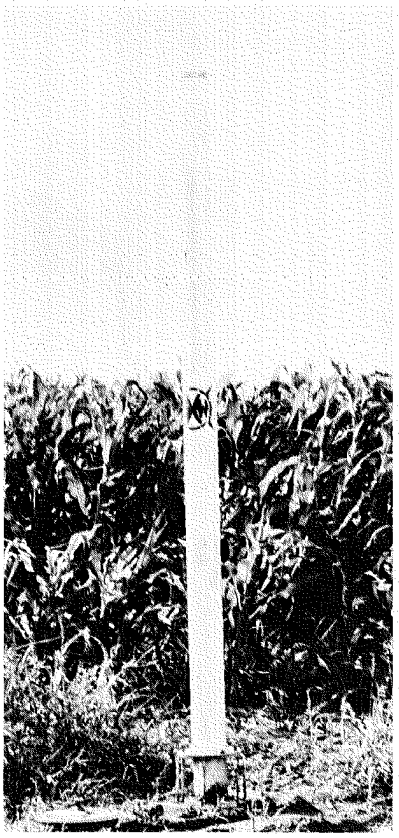

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Figure 3-64.--Typical capped vent.

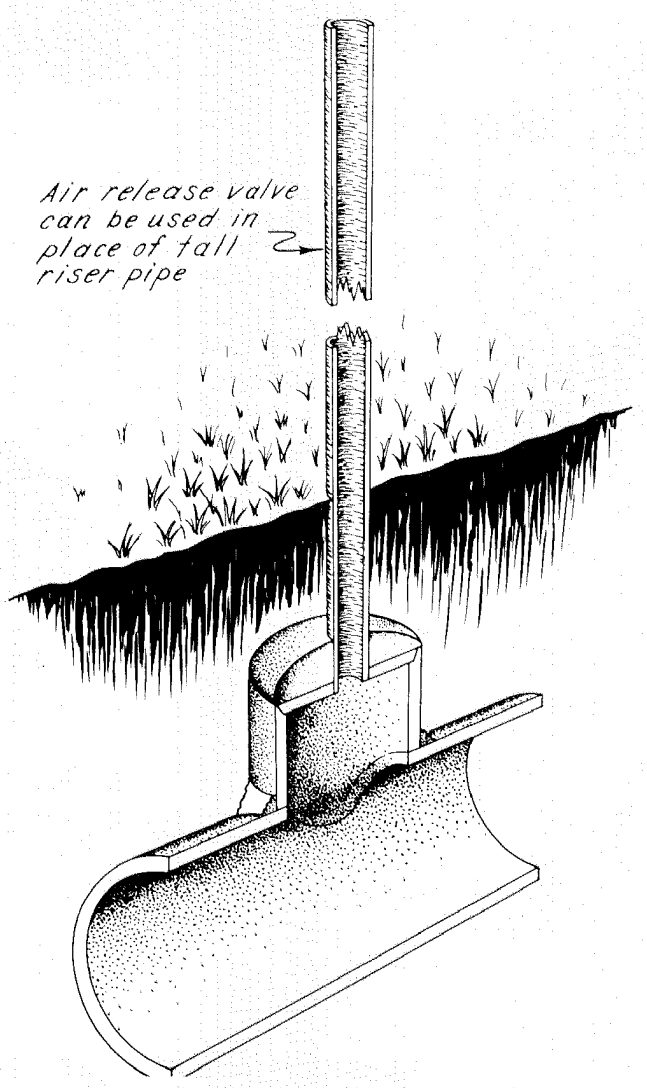

Figure 3-65.--Section of a capped vent.

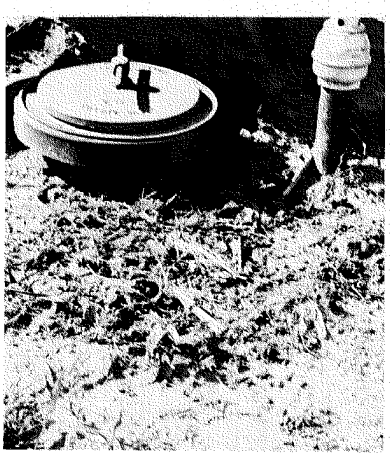

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Figure 3-66.--Closeup of air-release valve on right and alfalfa valve on left.

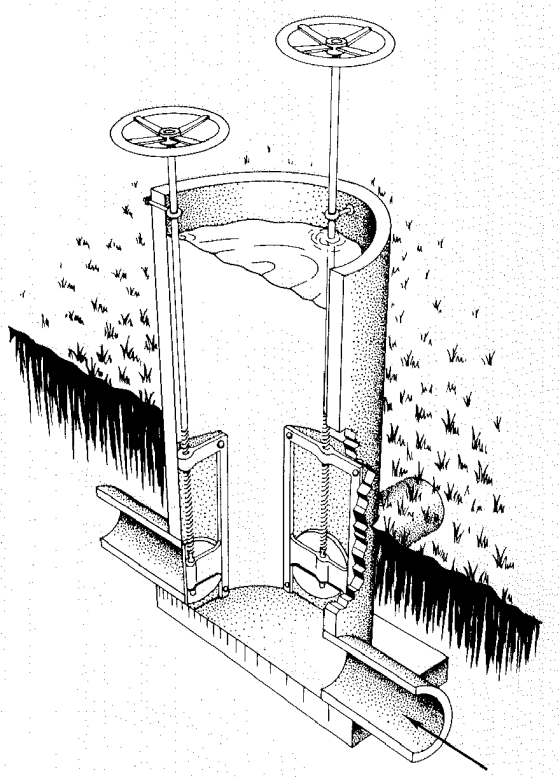

Figure 3-67.--Section of a concrete-pipe gate stand used to control flow into two laterals.

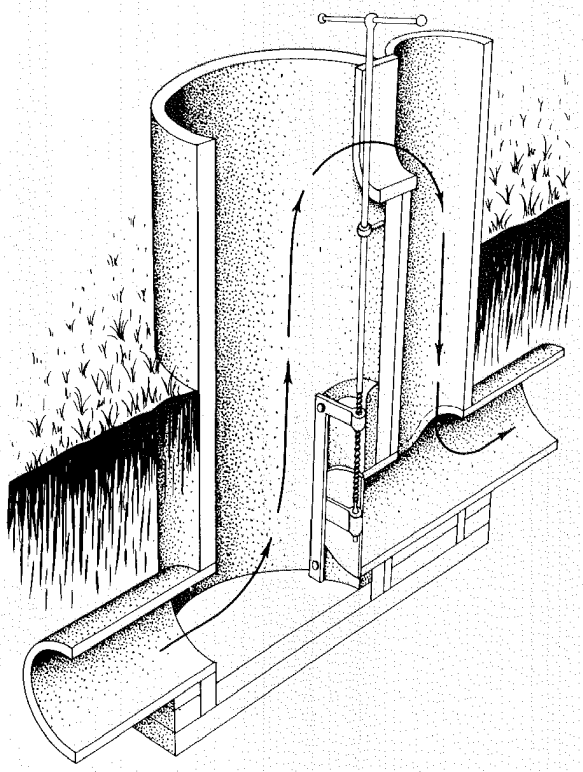

Figure 3-68.--Section of concrete-pipe overflow stand.

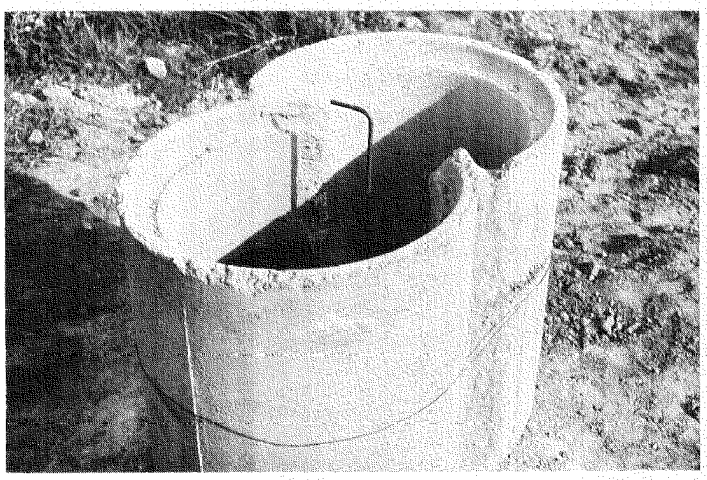

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Figure 3-69.--Concrete-pipe overflow stand.

discharge of hydrants immediately upstream is required, the gate valve is closed enough to keep the head upstream at about the overflow crest but with little or no overflow.

Float-Valve Stands.--Float-valve stands are similar to other stands except that a float valve is attached to the end of the pipe through which water enters the stand (fig. 3-70). The valve controls pressure in the reach of pipe immediately downstream from it. It releases into the stand only as much water as hydrants farther downstream are open to take. Thus, by opening and closing, the valve maintains a nearly constant water level in the stand, which is connected directly to the line or lines through which water flows downstream. When the lower outlets are closed, the float valve automatically closes and prevents excessive pressure from developing at the lower end.

Float-valve stands are useful on steep slopes and are usually installed at intervals of about 10 feet of drop in the line. They are especially good if a line is served directly from storage since the water can be controlled completely from the lower end of the line. Float-valve stands eliminate the need for many high overflow stands on steep slopes. They are usually made of reinforced concrete pipe having a minimum diameter of 30 inches. Generally about 2 feet of freeboard is desired and 1 foot is the minimum.

Outlets

Some type of outlet structure or hydrant is necessary in pipelines to deliver water to the land or into some distributing device. Hydrants are risers built from vertical sections of pipe, which are saddled over openings in the pipeline and permanently attached to it with a waterproof joint. Some kind of valve or gate is installed in the riser to regulate discharge through the hydrant.

Alfalfa Valves.--An alfalfa valve is a screw valve grouted to the top of a pipe riser (fig. 3-71). A handle and cap plate is attached to a threaded rod that moves up or down as the handle is turned. When the valve is closed, the cap plate fits the circular edge of the valve case to make it watertight. When the plate is lifted by turning the handle, water is released from all sides of the valve.

Alfalfa valves are used to distribute water directly to border strips, basins, or ditches. The valve top should be 3 to 4 inches below the ground surface to minimize interference with farming operations and to reduce erosion from the irrigation stream. Alfalfa valves can be fitted with hydrants for connecting to surface pipes (fig. 3-72).

Orchard Valves.--Orchard valves (figs. 3-73 and 3-74) are similar to alfalfa valves but have a smaller flow capacity and are so designed that they can be placed at the top of the riser, at the bottom, or at almost any point between. The preferred location is near the top.

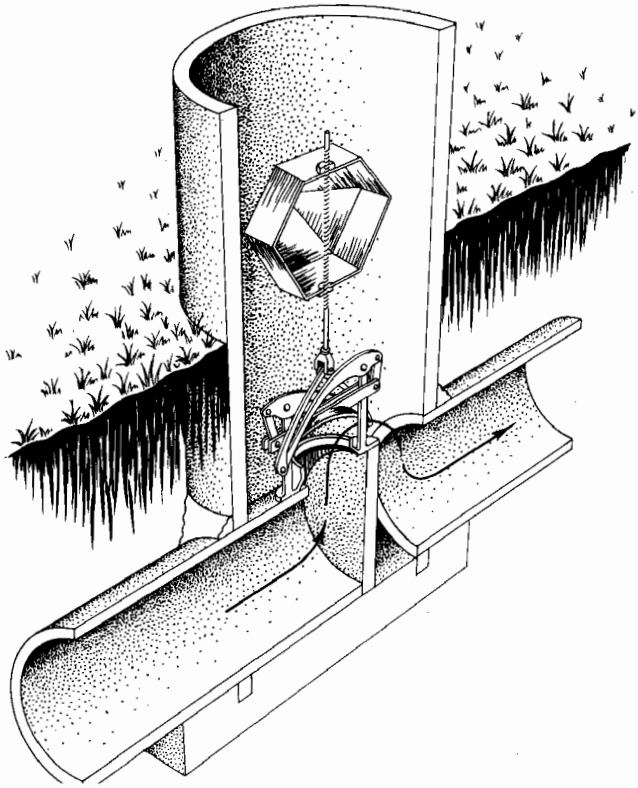

Figure 3-70.--Section of a float-valve stand.

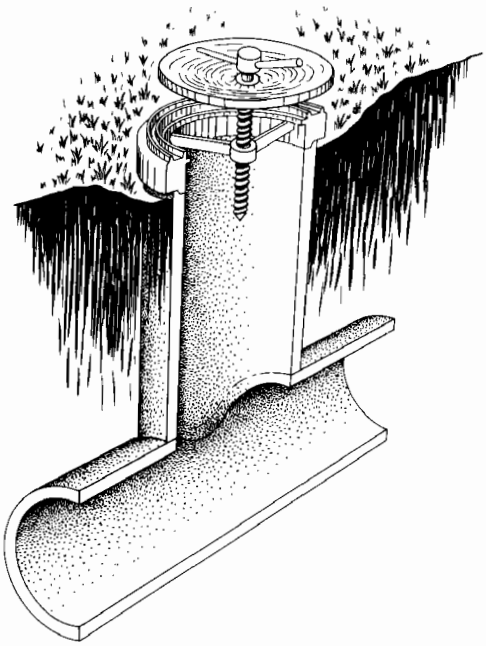

Figure 3-71.--Section of alfalfa valve mounted on concrete pipe.

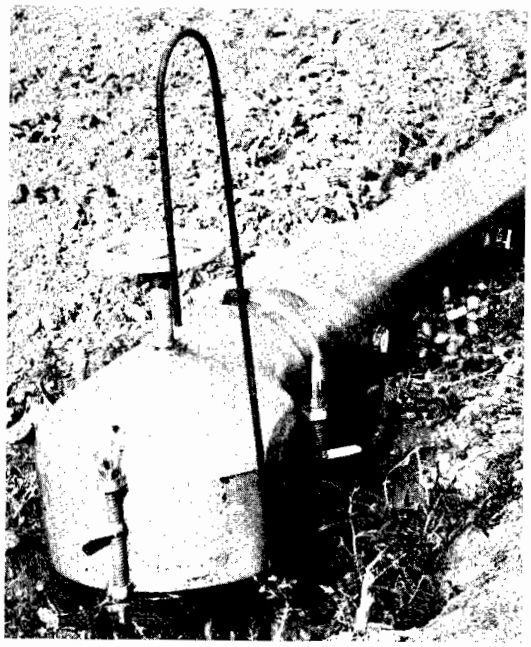

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Figure 3-72.--Hydrant attached to alfalfa valve for gated pipe.

Orchard valves are used instead of alfalfa valves if a smaller flow is acceptable. Because of their lower capacity, they are less likely to cause scour around the riser, the top of which should be level with the ground surface. It is also possible to place an additional length of pipe that has an opening on one side above the ground line to direct flow from the valve. Sheet metal stands and hydrants can also be fitted to orchard valves to deliver water into surface pipe or ditches.

Open-Pot Outlets.--In open-pot outlets the riser extends above the ground surface far enough for two or more slide-gate tubes to be installed close to the ground line. An orchard valve is placed below the slide gates (fig. 3-75). This kind of outlet distributes water through the gates to furrows and is used principally in orchard irrigation systems.

Orchard valves regulate flow into the pot, and the slide gates regulate flow into individual furrows. Good control can be had by adjusting the orchard valve to keep the water surface only an inch or two above the slide gates. The slide gates are placed inside the pot at ground elevation to minimize erosion of the adjacent soil. Size of the pot depends on the number and size of slide gates to be used. If line pressure is low enough that the pot will not overflow, an orchard valve is not needed in the riser. Then all the flow is controlled at the slide gates.

Capped Risers or Pot Outlets.--In these outlets (fig. 3-76) the top of the pot is capped, the slide gates are installed on the outside of the riser, and an orchard valve is not used. Flow is controlled by adjusting line pressure and by the slide gates. Capped-pot outlets are used only in irrigating orchards and permanent crops where small flows are distributed to the individual furrows.

The main advantage of capped-pot outlets is that leaves cannot fall into the pot and clog the slide gates and that an orchard valve is not needed. The disadvantages are less control of flow and that, because of the pressure, the jet of water from the slide gate may erode the adjacent soil. Special screw valves are available for use in place of the slide gates. These valves are designed to break the force of the jet and give a quiet nonerosive flow. Capped-pot outlets can be used where the pressure will not be more than 1 or 2 feet above the ground surface.

Surface-Pipe Outlets.--Surface-pipe outlets are risers extending above ground that are equipped with tubes or connections for attaching surface pipe to pipelines without using hydrants. Water for irrigating furrow crops is generally distributed by surface pipe. The risers must be high enough to produce the required pressure in the surface pipe. If the pressure in the pipeline is more than that required for the surface pipe, the outlet can be equipped with orchard valves to keep the riser from overflowing. In some low-pressure installations the connecting tube is equipped with a gate or the slide gates at the individual furrows are used as the controls.

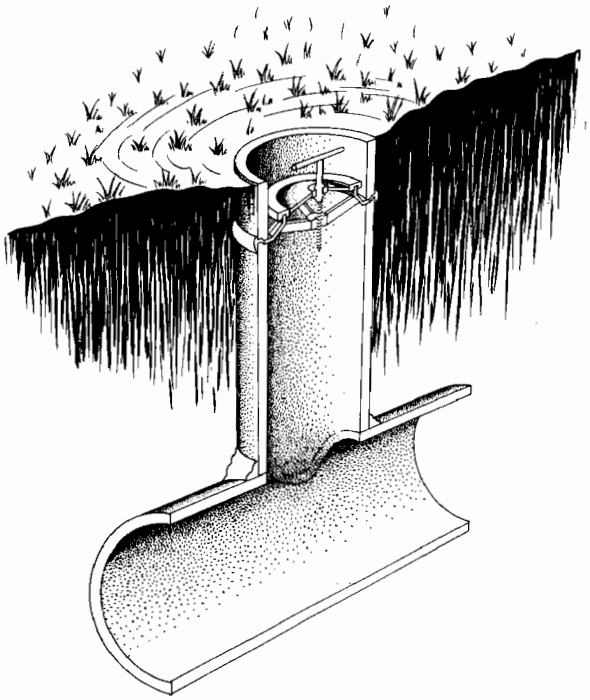

Figure 3-73.--Section of an orchard valve.

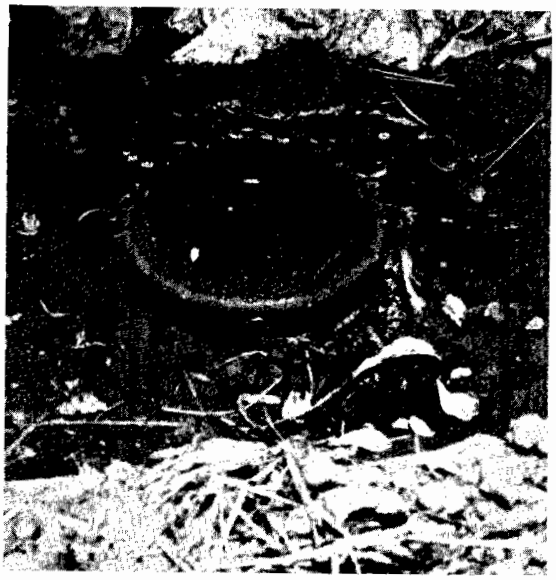

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Figure 3-74.--Orchard valve.

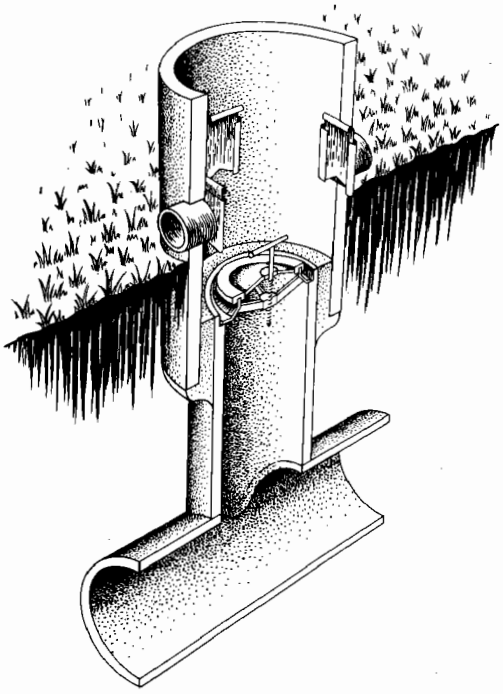

Figure 3-75.--Open-pot outlet with an orchard valve and slide-gate control.

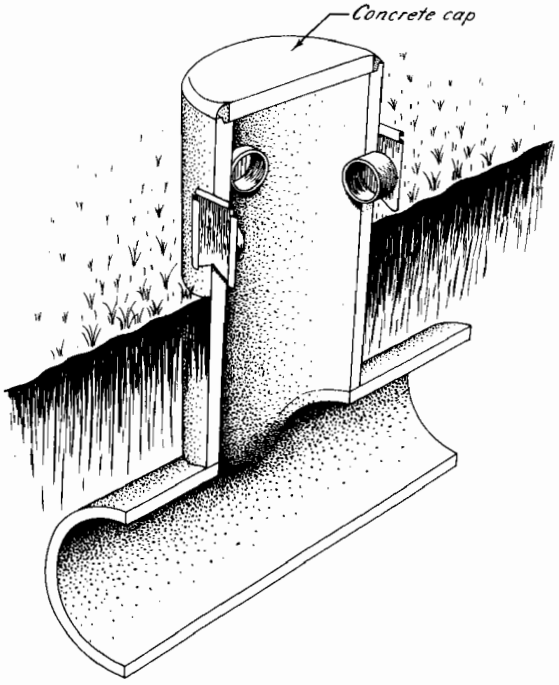

Figure 3-76.--Section of capped riser or pot outlet.

Water Disposal

The design of a farm irrigation system should provide facilities of adequate capacity to remove excess water from the irrigated land promptly and safely. The excess water may be waste from irrigation, surface runoff from rainfall, or excess percolation of either irrigation water or rainfall. It may also include leakage or seepage from parts of the conveyance system.

Some waste can be expected in using any of the graded-surface irrigation methods, but it can be kept to a minimum by good design and management. There is always the possibility of accidentally releasing excess irrigation water that must be controlled and removed. If you are planning to apply additional water for leaching or rice culture, you must also plan proper disposal facilities.

Storm runoff must be removed to protect the land, the irrigation system, and crop investment. This may require special erosion control measures or modifications in the design or layout of an irrigation system. Excess percolation of either irrigation water or rainfall may lead to a high water table that restricts root growth or promotes a saline or alkali condition. Seepage from canals, reservoirs, and sumps may waterlog adjacent land, and tile or open drains may be necessary to control the water table if natural internal drainage is not adequate.

To determine the kind of disposal needed, make a survey of the topography, kinds of soil, water table, and water sources. You must determine the areas from which water must be removed, the amount to be removed, the best way to remove it, and the points of disposal. Then design the water-disposal system according to approved standards.

Surface-Water Disposal

Excess surface water from irrigation waste or storm runoff must be removed for good plant growth. Generally open ditches or grassed waterways are used. Their location and capacity depend on the application method, rainfall amount and intensity, level of protection desired, topography, erodibility and internal drainage of the soils, as well as adequacy of the natural drains.

Effect of Irrigation Method

The application method particularly affects layout of the disposal system. Tail or waste ditches are needed at the lower end of furrows and borders to collect and remove excess surface water. For the contour-furrow method, grassed waterways are needed to pick up the water discharged from each furrow. For the contour-levee method, a waste ditch running downslope and connecting each leveed area is needed to remove waste water. On land leveled for contour benches, waterways drain the benches and generally some structures are needed to carry water between benches. For sprinkler irrigation, excess rainfall can be controlled and disposed of by terraces and diversions leading to grass waterways. On

flat land where there is no erosion hazard, shallow surface drains are used. In subirrigation systems, runoff water is disposed of through water-control structures placed in open ditches or tile drains. Pickup ditches must be provided to keep water from flowing directly from furrows or borders into irrigation head ditches.

Design Considerations

Tail ditches generally are shallow open drains large enough to carry away irrigation waste water and storm-water runoff. Storm runoff generally governs capacity. Grade should be as uniform as possible. Design the cross section to maintain an appreciable but nonscouring velocity during periods of maximum flow; on steep slopes drop structures may be required in the ditches. Banks of the waste-water ditch must be protected against erosion by surface-water inlet structures or by establishing vegetation on flattened slopes.

Subsurface-Water Disposal

Excess ground water must be removed by deep open ditches or tile to provide an effective root-zone depth. The source of the excess ground water, whether seepage from ditches and reservoirs or a high water table, has a bearing on the kind of subsurface disposal and its layout. High water tables must be lowered to a depth that permits a normal root zone for the crop to be grown.

Interceptor Drains

Interceptor drains generally consist of a single tile line or deep open drains installed along the base of a hill, parallel to a leaking canal, or around a leaking reservoir to intercept ground-water flow and prevent movement of water into a problem area. Tile drains are commonly used as interceptors because the drain must be located according to ground-water conditions, which generally do not correspond to field boundaries, fences, or property lines.

Relief Drains

Relief drains are used to lower a high water table in areas of slight or stagnant ground-water flow that cannot be intercepted effectively. They are usually planned as a series of lateral tile lines in a gridiron or herringbone pattern in which each line is connected to a main that leads to an open drain. Relief drains are laid parallel to the direction of ground-water flow.

Wells

A high water table in areas in which the soils are underlain by porous sand or gravel aquifers can be lowered by pumping. Often the pumped water can be used for irrigation if it is of satisfactory quality. Detailed subsurface and ground-water studies are needed to determine the possibility of sufficiently lowering the water table by this means.

In some areas in which artesian pressure maintains the water-table level at or near the ground surface, relief wells are used with subsurface drains. They are used if depth to the artesian aquifer is greater than practical drain depth and if the slowly permeable overlying material does not permit the ground water to move freely to the drain. Relief wells are connected to subsurface drains and extend through the slowly permeable soil layer into more permeable materials below. The water under pressure rises to the drain and is carried away. If the slowly permeable layer is only a few feet lower than the usual depth of the drains, relief wells can be put in open ditches by overdigging at intervals.

Outlets

Satisfactory outlets for disposal conduits must either be available or be planned for. They must be large enough to carry the expected maximum amount of water from disposal conduits. Typical outlets are large open ditches or natural streams. If topography does not permit disposing of waste water by gravity flow, pumping units and other needed appurtenant structures must be provided. The water can be drained to open pits or sumps and then be pumped to a surface outlet for disposal. In some places water collected in the sump can be used for irrigating lower fields or it can be pumped back and reused.

Water Measurement

Irrigation water must be measured if it is to be used efficiently. The principal objective of measuring irrigation water is to permit efficient distribution and application. By measuring water, a farmer knows how much water is applied during each irrigation.

Plan for enough measuring devices. Locate the main measuring device at the headgate or farm source of supply. If all the irrigation water is to be delivered to one field at a time, this main measuring device may be the only one needed for measuring the water supply to the various fields. But if the supply is divided between two or more ditches, measuring devices are needed at each ditch. Generally they can be built into other ditch structures, such as drops, checks, or turnouts. If the supply is delivered by pipelines, flow can be measured by various kinds of flow meters. It may be possible also to install an open-channel measuring device at the pipeline inlet structure or to install devices in overflow stand pipes or control boxes.

The various kinds of measuring devices are explained fully in chapter 9, Measurement of Irrigation Water, which gives information on constructing and installing various simple measuring devices and the necessary discharge tables and charts.

Irrigation Guides

The irrigation guides used in the Soil Conservation Service give the basic design criteria for all conservation irrigation methods recommended for specific combinations of soils, slopes, crops, water supply, and climate. They include groupings of all the major irrigated soils, the adapted crops, and the appropriate design criteria. They also provide some guides for conservation irrigation water management.

Area Covered

Irrigation guides generally are prepared on a problem or resource area basis. The primary factor determining the size of the area covered is similarity in design criteria based on soils, topography, and climate. Usually the smallest area included in a guide is a soil conservation district and the largest area is a State. All combinations of local conditions generally are covered in a guide so that an irrigation planner knows the irrigation practices recommended for any conditions in the area.

Content

Irrigation guides do not include all the technical standards needed for or associated with a complete conservation program on irrigated land. They give necessary design information pertaining to the soil in a given field, the crop to be irrigated, and the requirements for water application. They do not include technical standards for land leveling, ditch construction, canal lining, irrigation structures, and other hydraulic design features. The information in the guides is given under three main headings--soils, crops, and irrigation specifications.

Soils

Soils having similar physical characteristics for irrigation are grouped together. This grouping takes into account depth, texture, permeability, water-holding capacity, and intake characteristics. Symbols for soils are the same as those on the soil maps for the area. The effective soil depth is tabulated by successive layers or horizons beneath the surface. These depths are average depths for all the soils in a group. The available water holding capacity is shown for each depth or horizon.

Crops

The crops usually considered to be adapted locally to each soil group are listed as well as the average soil depth from which the crops extract moisture. The guide lists the recommended amount of moisture to be replaced in a normal irrigation for each crop listed, the design consumptive-use rate of each crop, and the irrigation frequency during the period of maximum consumptive use. The irrigation frequency is the recommended maximum number of days that can be allowed between irrigations during periods of maximum water use without rainfall.

Irrigation Specifications

This section of the guide provides the information necessary to determine the best irrigation method and the basic data for its design. The conservation irrigation methods suited to each soil group and the crops to be grown are listed as well as the intake-family design intake rate for furrows and corrugations and the design application rate for sprinklers. Stream sizes for the adapted surface methods are given for the design slope groups and the maximum length of run, estimated field efficiency, gross irrigation application, and estimated number of hours required to apply the water.

Use

For good irrigation water management, a farm irrigation system must be designed to fit the crops and soils to be irrigated. The local irrigation guide provides the basic information needed to design such a system. After determining the kind of soil in the field to be irrigated and selecting the crop or crops, you must choose a method of applying irrigation water. The guide shows the method or methods of water application that can be used successfully for the crop and site conditions in the field to be irrigated and the basic design requirements.

The following example shows how to use an irrigation guide. Figure 3-77 is a guide for all irrigated sections of Kansas. The soil is Crete silty clay loam, the slope is 0.2 percent, and the crop to be irrigated is corn. Column 5 indicates that, for 0.0 to 0.25 percent slopes, corn grown on this soil has a moisture-extraction depth of 4 feet, requiring a net application of 4.3 inches of water for a normal irrigation (column 6). The peak-period consumptive-use rate or design rate for corn is 0.29 inches per day (column 7), and the irrigation frequency for the period of maximum consumptive use is 15 days (column 8). Column 9 shows that corn grown on this soil can be either furrow irrigated or sprinkler irrigated. Now assume that the farmer prefers the furrow method of water application and will plant his corn on a 40-inch spacing. Find the 40-inch spacing in column 12, and note to the left that the maximum allowable stream is 50 gallons per minute (column 11) and that the estimated average intake is 1.3 gallons per minute per 100 feet (column 10). Follow the 40-inch line to the right. Column 13 shows that the maximum length of run is 1,870 feet; the estimated efficiency is 70 percent (column 14), requiring 6.2 inches for the gross irrigation application (column 15). The estimated time required to make this application is 14 hours (column 16).

You must then fit the design information from the guide to the field to be irrigated. If the field is considerably longer than the maximum permissible length of run, you must use two shorter lengths of run to irrigate the field properly. Other soil conditions in the field may necessitate further revisions. If the extraction depth is less than 4 feet because of soil conditions, the amount of moisture to be replaced at each irrigation is also less, which in turn affects the gross application, the time estimated for applying the irrigation, and the length of run.

U. S. DEPT. OF AGRICULTURE
SOIL CONSERVATION SERVICE

IRRIGATION GUIDE

SOILS			CROPS					IRRIGATION SPECIFICATIONS							
SOIL MAP-PING SYMBOL	PROFILE DESCRIPTION	AVAILABLE MOISTURE HOLDING CAPACITY by feet of depth inches	LOCALLY ADAPTED CROPS	MOIS-TURE EXTRAC-TION DEPTH feet	NET MOISTURE TO BE REPLACED EACH IRRIGA-TION inches	PEAK PERIOD CONSUMPTIVE USE RATE in./day	IRRIGATION FREQUENCY DURING PERIOD OF MAXIMUM CONSUMPTIVE USE days	ADAPTED CONSERVATION IRRIGATION METHODS	INTAKE FAMILY Border or Flooding Sprinkler in./hr. Furrow or Corrugation g.p.m./100'	Stream Size Border or Flooding Unit Stream c.f.s. Furrow or Corrugations Max. Stream g.p.m. Sprinklers in./hr.	USUAL BORDER WIDTH feet FURROW OR CORRUGATION SPACING inches	MAX. LENGTH OF RUN feet	EST. FIELD EFF. %	GROSS IRRIGATION APPLICATION inches	ESTIMATED TIME REQUIRED hours
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						Slope Group 0.0% to 0.1% (Design Slope Level)									
	Crete silty clay loam	1 - 2.2	Alfalfa	6.0	6.2	.28	22	Level Bord.	0.3	.0023	-	1320	80	7.8	8.0
	Richfield silt loam	2 - 4.4													
	Farnum loam	3 - 6.4	Corn	4.0	4.3	.29	15	Level Bord.	0.3	.0040	-	1320	70	6.2	3.6
	Elmo silty clay loam	4 - 8.6													
	Pond Creek silt loam	5 -10.8	Sorghum	4.0	4.3	.29	15	Level Bord.	0.3	.0040	-	1320	70	6.2	3.6
	Harney silt loam	6 -12.3													
	Bethany silt loam		Sugar Beets	4.0	4.3	.29	15	Level Bord.	0.3	.0040	-	1320	70	6.2	3.6
	Lubbock silty clay loam														
			Wheat	4.0	4.3	.25	17	Level Bord.	0.3	.0040	-	1320	70	6.2	3.6
	Deep, well drained upland soils with loam to silty clay loam surface layers; clay loam to silty clay subsoils and permeable substrats. (0% to 7% slopes)		Soy Beans	3.0	3.2	.30	11	Level Bord.	0.3	.0057	-	1320	65	4.9	2.0
			Grass-Tame	3.0	3.2	.26	12	Level Bord.	0.3	.0057	-	1320	65	4.9	2.0
						Slope Group 0.0% to 0.25% (Design Slope 0.2%)									
			Alf.& S.Cl.	4.6	5.0	.29	17	Border	0.3	.0020	30--60	2640	70	7.2	8.4
				6.0	6.2	.28	22	Sprinkler	0.2 B	-	-	-	70	8.9	-
									0.3 C	-	-	-	70	8.9	-
			Corn	4.0	4.3	.29	15	Furrow	1.1	40	36	1660	70	6.2	15.0
									1.3	50	40	1870	70	6.2	14.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
	Roxbury silty clay loam								0.3 C	-	-	-	70	6.2	-
	Dale silt loam, clay loam		Sorghum	4.0	4.3	.29	15	Border(Dr.)	0.3	.0025	30--60	2640	70	6.2	5.8
								Furrow	0.8	20	20	1140	70	6.2	11.5
									1.0	30	30	1420	70	6.2	14.0
	Detroit Silty clay loam								1.3	50	40	1870	70	6.2	14.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
	Deep, well drained alluvial soils with silt loam to silty clay loam surface layers; clay loam to silty clay loam subsoils and permeable substrats. (0% to 2% slopes)		Sugar Beets	4.0	4.3	.29	15	Furrow	0.8	20	22	1140	70	6.2	12.5
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Wheat	4.0	4.3	.25	17	Border	0.3	.0025	30--60	2640	70	6.2	5.8
								Furrow	1.0	30	30	1420	70	6.2	14.0
									1.3	50	40	1870	70	6.2	14.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Soy Beans	3.0	3.2	.30	11	Border(Dr.)	0.3	.0035	30--60	2640	70	4.6	2.1
								Furrow	1.0	20	20	980	70	4.6	6.8
									1.2	30	30	1240	70	4.6	8.5
								Sprinkler	0.2 B	-	-	-	70	4.6	-
									0.3 C	-	-	-	70	4.6	-
			Dry Beans	3.0	3.6	.28	11	Furrow	1.0	20	20	980	70	4.6	6.8
									1.2	30	30	1240	70	4.6	8.5
			Grass	3.0	3.2	.26	12	Border	0.3	.0035	30--60	2640	70	4.6	2.1
								Sprinkler	0.2 B	-	-	-	70	4.6	-
									0.3 C	-	-	-	70	4.6	-
						Slope Group 0.25% to 0.5% (Design Slope 0.4%)									
			Alf.&S.Cl.	3.7	4.0	.29	14	Border	0.3	.0025	30--60	2640	70	5.7	5.3
				6.0	6.2	.28	22	Sprinkler	0.2 B	-	-	-	70	8.9	-
									0.3 C	-	-	-	70	8.9	-
			Corn	4.0	4.3	.29	15	Furrow	0.8	25	36	1290	70	6.2	20.5
									0.8	25	40	1290	70	6.2	23.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Sorghums	3.7	4.0	.29	14	Border(Dr.)	0.3	.0025	30--60	2640	70	5.7	5.3
				4.0	4.3	.29	15	Furrow	0.7	20	20	1140	70	6.2	13.0
									0.8	25	30	1290	70	6.2	17.0
									0.8	25	40	1290	70	6.2	23.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Sugar Beets	4.0	4.3	.29	15	Furrow	0.7	20	22	1140	70	6.2	14.5
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Wheat	3.7	4.0	.25	16	Border	0.3	.0025	30--60	2640	70	5.7	5.3
				4.0	4.3	.25	17	Furrow	0.8	25	30	1290	70	6.2	17.0
									0.8	25	40	1290	70	6.2	23.0
								Sprinkler	0.2 B	-	-	-	70	6.2	-
									0.3 C	-	-	-	70	6.2	-
			Soy Beans	3.0	3.2	.30	11	Border(Dr.)	0.3	.0028	30--60	2640	70	4.6	3.9
								Furrow	0.9	20	20	980	70	4.6	7.5
									1.0	25	30	1110	70	4.6	10.0
								Sprinkler	0.2 B	-	-	-	70	4.6	-
									0.3 C	-	-	-	70	4.6	-
			Dry Beans	3.0	3.2	.28	11	Furrow	0.9	20	20	980	70	4.6	7.5
									1.0	25	30	1110	70	4.6	10.0

Figure 3-77.--Irrigation guide for all irrigated sections of Kansas.

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Section 15

IRRIGATION

Chapter 4

Border Irrigation

Soil Conservation Service
United States Department of Agriculture

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 4--BORDER IRRIGATION

CONTENTS

Page

Description..... 4-1
Adaptability..... 4-1
Layout considerations..... 4-1
  Border strip width..... 4-1
  Border strip length..... 4-2
  Border ridge height..... 4-3
Design considerations..... 4-3
  Soil intake characteristics..... 4-3
  Roughness coefficient..... 4-5
Kinds of border irrigation..... 4-6
  Level border..... 4-6
    Adaptability..... 4-6
    Advantages..... 4-6
    Limitations..... 4-6
    Design assumptions..... 4-7
    Design equations..... 4-7
    Design limitations..... 4-12
    Construction requirements..... 4-13
    Design procedure..... 4-15
    Design charts..... 4-16
  Graded border..... 4-16
    Adaptability..... 4-18
    Advantages..... 4-18
    Limitations..... 4-18
    Design assumptions..... 4-18
    Design equations..... 4-19
    Relationship to unit stream concept..... 4-20
    Recession-lag time..... 4-21
    Design limitations..... 4-24
    Field efficiency..... 4-32
    Design procedure..... 4-34
    Design charts..... 4-34
    Use of end blocks..... 4-38
  Guide border..... 4-42
    Adaptability..... 4-42

Page

Advantages..... 4-42
Limitations..... 4-43
Design assumptions..... 4-43
Design equations..... 4-43
Design limitations..... 4-43
Construction requirements..... 4-46
Appendix A. Level border irrigation design charts for n = 0.04.... 4A-1
Appendix B. Level border irrigation design charts for n = 0.15.... 4B-1
Appendix C. Level border irrigation design charts for n = 0.25.... 4C-1
Appendix D. Graded border irrigation design charts for n = 0.04... 4D-1
Appendix E. Graded border irrigation design charts for n = 0.15... 4E-1
Appendix F. Graded border irrigation design charts for n = 0.25... 4F-1

Figure

4-1 Intake families for border irrigation design..... 4-4
4-2 Typical advance curve with computation of average intake opportunity time..... 4-10
4-3 Chart for estimating efficiency of level border irrigation... 4-11
4-4 Chart for estimating depth of flow in level borders with n of 0.15..... 4-14
4-5 Sample design chart for level border irrigation..... 4-17
4-6 Diagram of recession-lag time..... 4-21
4-7 Depth of flow and recession-lag time in graded border irrigation..... 4-23
4-8 Sample design chart for graded border irrigation..... 4-37
4-9 Diagram of end block length extension..... 4-40
4-10 Stream size and length of run relationship for guide border design when n = 0.15..... 4-44
4-11 Stream size and length of run relationship for guide border design when n = 0.25..... 4-45

Table

4-1 Recommended maximum border strip width..... 4-2
4-2 Values of parameters a, b, and c for standard intake families 4-4
4-3 Intake opportunity time for net depth of application for each family..... 4-5
4-4 Ratio of T_t to T_n for various efficiency values..... 4-12
4-5 Conversion factors for depth of flow and recession-lag time for various roughness coefficients..... 4-22
4-6 Recession-lag time in low-gradient borders..... 4-26
4-7 Depth of flow in low-gradient borders..... 4-27
4-8 Maximum value of Q_u for nonsod and sod crops by slope..... 4-28
4-9 Allowable unit-width irrigation stream for given maximum depth of flow..... 4-29
4-10 Minimum value of Q_u/L for various n values by slope..... 4-30

Page

4-11 Maximum slopes for graded border irrigation as limited by minimum depth of flow requirements or by a minimum border length of 100 feet..... 4-31
4-12 Suggested design efficiency for graded border irrigation by slope and intake family..... 4-33
4-13 Maximum border lengths for using end blocks by slope and net depth of application..... 4-38
4-14 Intake and roughness factors for estimating potential runoff..... 4-39
4-15 Required time of irrigation and gross depth of application for guide borders on 0.1 intake family soils..... 4-47
4-16 Required time of irrigation and gross depth of application for guide borders on 0.3 intake family soils..... 4-48
4-17 Required time of irrigation and gross depth of application for guide borders on 0.5 intake family soils..... 4-49
4-18 Required time of irrigation and gross depth of application for guide borders on 1.0 intake family soils..... 4-50

NOMENCLATURE

A = Area (square feet)

a = Intercept of accumulated intake at unit time

b = Exponent of time in intake equation

c = Constant in intake equation

C_d = Flow depth conversion factor

C_t = Recession-lag time conversion factor

d_1 = Depth of flow at head of run (feet)

d_a = Average depth of flow (feet)

d_n = Normal depth of flow (feet)

E = Field application efficiency (percent)

F = Accumulated intake (inches)

F_a = Average depth of intake (inches)

F_g = Gross depth of application (inches)

F_n = Net depth of application (inches)

I_F = Intake family

K = Site factor

L = Border length (feet)

L_e = Length extension with end blocks (feet)

L_t = Length of advance (feet)

n = Roughness coefficient in the Manning equation

Q = Irrigation stream for a border strip (cubic feet per second)

Q_i = Intake rate during the recession-lag period (cubic feet per second)

Q_o = Flow of water down the border strip (cubic feet per second)

Q_u = Irrigation stream per foot of strip width (cubic feet per second)

q = Unit irrigation stream (cfs per 100 square feet)

r = Hydraulic radius

r_i = Intake factor for runoff prediction

r_n = Roughness factor for runoff prediction

s_l = Slope of water surface or hydraulic slope (feet per foot)

s_i = Hydraulic grade (feet per foot)

s_o = Slope of border strip or irrigation slope (feet per foot)

T_a = Time of application (minutes)

T_L = Recession-lag time (minutes)

T_n = Time required for the net depth of application (F_n) to infiltrate the soil (minutes)

T_o = Intake opportunity time (minutes)

T_t = Time of advance (minutes)

V = Volume of water on border strip (cubic feet)

W = Border strip width (feet)

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 4. BORDER IRRIGATION

Description

Border irrigation is a method of controlled surface flooding. The field to be irrigated is divided into strips by parallel dikes or border ridges, and each strip is irrigated separately. Water is introduced at one end and progressively covers the entire strip. Three different kinds of border irrigation--level, graded, and guide--are used depending on topography, soil, water supply, and other factors. Each kind has features that are advantageous under some circumstances and disadvantageous under others. In planning an irrigation system for a farm and selecting a method of applying water to the soil, the advantages and limitations of each of the three kinds of border irrigation must be considered carefully. Level, graded, and guide border irrigation are discussed in detail later in this chapter.

Adaptability

Border irrigation is suited to all crops that are not damaged by inundation for short periods. It can be used with almost any crop if site conditions are such that the needed degree of water control can be obtained. It can be used on nearly all irrigable soils but is best suited to soils whose intake rates are neither extremely low nor extremely high.

Layout Considerations

In addition to the limits on design imposed by hydraulic factors (discussed later in this chapter for each of the three kinds of border irrigation), design may be limited by practical layout and construction considerations. The empirical limits suggested by these considerations are not precise, mandatory requirements, but they are guides for design. They should be exceeded only with great caution.

Border Strip Width

Border strip widths suitable for any particular field depend on (1) size of the available irrigating stream, (2) amount of cross slope that must

be removed, (3) kind of equipment used, and (4) accuracy of land leveling as related to the normal depth of flow expected. The border strips must be wide enough to permit efficient operation of farm equipment. Mowers and rakes, for example, can be operated where there is a small amount of overlap on passes. Other equipment such as plows, seeders, and cultivators requires a definite width for each pass. The border strip must be wide enough to accommodate at least one pass of a plow, seeder, cultivator, etc., but it is desirable for the strip to be wide enough for an even number of passes.

A width of about 15 feet is the practical minimum for each strip on hay and grain fields. Narrower strips are satisfactory for pastures. For row crops grown on level border strips, the strips usually must be wide enough to allow for at least two passes with four-row equipment.

Maximum width is influenced largely by the difficulties in keeping water spread over the entire width of a strip. Under normal construction, wide border strips are expected to have greater differences in cross slope elevation than narrower strips. As flow depth decreases because of increased slope, minor surface irregularities in the border strip may cause incomplete water coverage. For this reason, the border strip width must be reduced as irrigation grade increases (see table 4-1).

Table 4-1.--Recommended maximum border strip width

Irrigation grade	Maximum strip width
Feet per foot	Feet
Level	200
0.0 -0.001	120
0.001-0.005	60
0.005-0.010	50
0.010-0.020	40
0.020-0.040	30
0.040-0.060	20

Border Strip Length

Long border strips are easier to farm than short strips because fewer turns by farm equipment are required. Some of the factors that can determine the maximum length of run in specific fields are flow hydraulics, field boundaries and barriers such as stream channels and drainage ditches, and changes in soil and in land slope. Border strips should not be laid out across two or more soil types that have different intake characteristics or different available water holding capacities, or both. Also, border strips should not extend across slopes that differ greatly from each other in steepness and length.

Occasionally, slope, soil, and hydraulic conditions are such that an extremely long run seems feasible. However, the time required to patrol long runs and the difficulties in determining and making needed adjustments in stream size usually make these runs impractical. Length of run in excess of a quarter mile seldom is satisfactory.

Border Ridge Height

On noncohesive soils, border ridges with a settled height of more than 8 inches are difficult to construct and maintain without making them excessively wide. Greater heights are practical on some cohesive soils, particularly if farm equipment does not need to be operated across the ridges. If large border ridges are planned, however, special provisions must be made for planting and harvesting of crops, and controlling of weeds. Also, it generally is difficult to wet through border ridges that are more than 1 foot high. In addition, where salinity is a problem, salt can accumulate in the ridge crest. The higher the ridge, the more pronounced the salt accumulation is likely to be.

Border ridges must be constructed so that crown width is at least as great as ridge height. Side slopes should be no steeper than 2-1/2 horizontal to 1 vertical. On noncohesive soils the side slopes should be no steeper than 3 to 1. Border ridges at the edge of field benches should be a little wider and higher than those normally required on unbenched fields.

Design Considerations

Soil Intake Characteristics

Designs for the border method depend on knowing the intake characteristics of the soils to be irrigated. Although each kind of soil has its own intake characteristics, the differences between some soils are so minor that, for all practical purposes, several soils can be considered together. For design purposes, almost all soils can be placed in one of eight intake groups called intake families. Each family has been assigned a number such as 0.1, 0.3, 0.5, etc., that represents the approximate value of the basic intake rate for soils in these families. These families are described by equations that have the general form:

$$F = a\ T_o^b + c$$

Table 4-2 gives the values of the parameters a (intercept of accumulated intake at unit time), b (exponent of time), and c (constant) for each family.

Table 4-2.--Values of parameters a, b, and c for standard intake families

Intake family	a	b	c
0.1	0.0244	0.661	0.275
0.3	.0368	.721	.275
0.5	.0467	.756	.275
1.0	.0701	.785	.275
1.5	.0899	.799	.275
2.0	.1084	.808	.275
3.0	.1437	.816	.275
4.0	.1750	.823	.275

Figure 4-1 shows the accumulated intake curve for each intake family and the range of values associated with each curve.

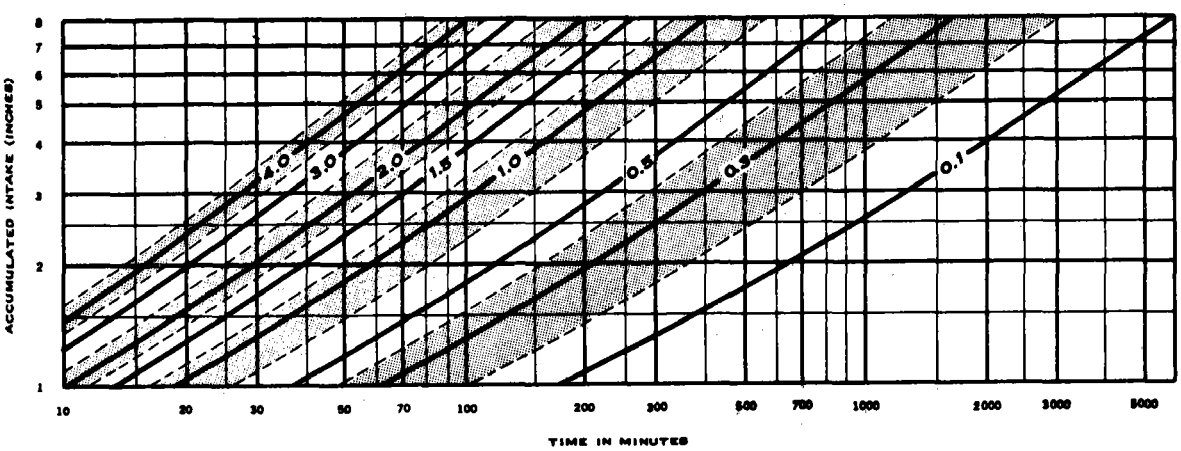


Figure 4-1.--Intake families for border irrigation design

Intake characteristics associated with border irrigation usually are measured by cylinder infiltrometers. They also are estimated by measuring the flow onto a border strip together with measuring the depth of water temporarily stored on the soil surface. For any given time period during which water is advancing down a border strip, the total volume of intake in the soil is equal to the volume of water run onto the border strip minus the volume temporarily stored on its surface. A series of intake measurements can be compared with those in figure 4-1 to determine the correct intake curve to use for design. (Soils that crack on drying or in which there are extreme differences between profile horizons may require special intake evaluations.)

Most irrigated soils can be associated with one of the intake families for design purposes. The design procedure is greatly simplified by this association, for standard charts and tables can then be prepared to show

the intake characteristics and design requirements by families. One example is the intake opportunity time required for various net depths of application for each intake family (see table 4-3).

Table 4-3.--Intake opportunity time for net depth of application for each family

Intake family	Net depth of application (F_n) in inches							
	1	1.5	2	2.5	3	4	5	6
	Minutes							
0.1	169	374	628	923	1,255	2,014	2,886	3,858
0.3	62.4	129	208	296	392	604	841	1,100
0.5	37.6	75.3	119	166	217	328	450	580
1.0	19.6	38.3	59.2	81.8	106	158	214	273
1.5	13.6	26.3	40.4	55.5	71.6	106	143	181
2.0	10.5	20.1	30.7	42.1	54.2	79.7	107	136
3.0	7.3	13.8	21.0	28.7	36.8	53.9	72.2	91.3
4.0	5.6	10.6	16.1	22.0	28.1	41.1	54.8	69.2

Roughness Coefficient

In the design procedures discussed later in this chapter, various forms of the Manning equation are used to describe the hydraulics of the three kinds of border irrigation. One of the important parameters in this equation is the roughness coefficient (n). This coefficient expresses the flow-retardance effects of different hydraulic boundary conditions. Some crops retard flow more than others. Height, density, shape, and stem stiffness of plants are some factors that affect retardance. Smooth, bare soil, such as found in noncultivated, oil-mulch-treated citrus groves, has the lowest hydraulic roughness of any condition normally associated with the border method of irrigation.

More studies are needed to define adequately the proper value of n for different (1) crops, (2) stages of crop growth, and (3) degrees of roughness of the soil surface. Until more information is available, based on field experience an n value of 0.04 can be used for smooth, bare soil surfaces and also for row crops irrigated by the level border method. An n value of 0.10 usually is accepted for drilled small grain crops if the drill rows run lengthwise of the border strip. An n value of 0.15 is suggested for alfalfa, mint, broadcast small grain, and similar crops. Dense sod crops and small grain crops that are drilled across the border strip can be expected to have an n value of about 0.25.

If design is limited by a maximum allowable flow depth, a conservatively high value of n should be used. On the other hand, if the design is limited by a minimum allowable stream size, a conservatively low n value should be chosen.

Kinds of Border Irrigation

Level Border

Water application is accomplished by ponding. The border strips have no slope in the direction of irrigation, and they are closed at the ends so the water is retained and absorbed into the soil. The irrigation stream must be large enough to cover the entire strip in a relatively small proportion of the time required for the soil to absorb the desired amount of water. The stream is turned off when the desired volume of water has been applied to the strip.

Adaptability

There are almost no crop restrictions with level border irrigation. It is widely used for close-growing crops such as alfalfa and other legumes, grasses, small grains, mint, and rice. It is used for row crops that can withstand some inundation, such as sugar beets, corn, grain sorghum, and cotton, and for other row crops if they are planted on beds so they will be above the water level. It also is well suited to the irrigation of tree crops, grapes, and berries.

This kind of irrigation is best suited to soils that have moderate to low intake rate (soils in the 2.0 intake family or less). It is the best way of applying water to soils that have an extremely low intake rate. It also can be used on soils that have a moderately high to high intake rate, but border strip areas may become undesirably small on the soils of higher intake rate.

Level border irrigation is best suited to smooth, gentle, uniform land slopes. Undulating or steep slopes can be prepared for this kind of irrigation, however, if the soils are deep enough to permit needed land leveling.

Advantages

Many different kinds of crops can be grown in sequence without making major changes in design, layout, or operating procedures. High application efficiency can be obtained easily. In fact, soils of low intake rate that are difficult to irrigate with graded or guide borders can be irrigated with level borders at an efficiency approaching 100 percent. No irrigation water is lost by runoff and little by deep percolation, and maximum use can be made of rainfall. Leaching operations are made easier; leaching can be done without changing either layout or method of operation. In addition, level border irrigation requires little labor; it is ideally suited to mechanization and can be adapted easily to automation or operated efficiently by inexperienced workers.

Limitations

Limitations are few; however, accurate land leveling is generally needed. Also, maintenance of a level surface is essential; such maintenance may require changing tillage operations or using special tools, or both. An adequate border ridge height may be difficult to maintain if the ridge

is constructed of sandy soil or of a fine-textured soil that cracks when dry. Excessive ponding and possible scalding can occur if the system is poorly managed. In some areas special provisions must be made for surface drainage. Drop structures, lined ditches, or pipelines may be required for adequate water control on steep slopes that require benching. Relatively large irrigating streams are needed; in some places two or more turnouts per border strip must be installed so that water is supplied at the needed rate without causing erosion.

Design Assumptions

The hydraulic principles of level border irrigation are comparatively simple. Water is applied to one end of the border strip at a rate that will provide coverage of the entire strip in a relatively short time. The water is then ponded until it infiltrates the soil. If a border strip could be covered instantaneously, all points on the strip would have the same intake opportunity time. Also, if the amount of water applied is limited to the net amount required, it should be possible to get an application efficiency of 100 percent. It is, of course, impossible to get instantaneous coverage of the border strip area. Therefore, some parts of the strip have a longer intake opportunity time than other parts, and efficiency decreases as these time differences increase.

Studies of the distribution of intake under various rate-of-advance curves show that a border strip can be irrigated satisfactorily if the following conditions are met:

1. The volume of water delivered to the border strip is adequate to cover the area of the border strip to an average depth that is equal to the gross irrigation application.
2. The intake opportunity time at the last point covered in the border strip is equal to the time required for the net irrigation to enter the soil.
3. The longest intake opportunity time at any point on the border strip is such that there is no detrimental deep percolation.
4. The depth of flow is no greater than can be contained by the border ridges.

The first condition refers to the gross application; the second condition depends on the net application. The difference between the gross and the net applications is equal to the deep percolation in the parts of the border strip having opportunity for intake in excess of the net irrigation.

Design Equations

Equations representing the flow of water on level borders are most useful if they pertain to a border strip 1 foot wide. On a unit-width border strip, the volume of water run onto the strip is equal to 60 Q_uT_a cubic feet. If the volume is given in inches of average depth over the area, volume is written as 720 Q_uT_a square feet-inches. The volume run onto the strip is equal to the volume of intake (F_aL_t) plus the volume of water in temporary surface storage (12 d_aL_t). From this

relationship a rate-of-advance equation can be developed.

$$720\ Q_u T_t = F_a L_t + 12\ d_a L_t \qquad \text{(Eq. 4-1)}$$

or

$$L_t = \frac{720\ Q_u T_t}{F_a + 12\ d_a} \qquad \text{(Eq. 4-2)}$$

Equation 4-2 is valid when the time of application (T_a) equals or exceeds the advance time (T_t). If the water is turned off before the advancing front has reached the end of the border strip, the actual rate of advance may be slightly slower than indicated.

The average depth of intake (F_a) can be developed most easily for a condition of uniform rate of advance. Likewise, the average depth of flow (d_a), or the average depth of surface storage, can be calculated most readily for a condition of flow over an impervious surface. Since the rate of advance is curvilinear rather than linear, however, the average depth of intake is underestimated. On the other hand, the average depth of surface storage correspondingly is overestimated. The indicated surface storage depth is greater than the actual surface storage depth because part of the water infiltrates the soil during advance. Since the two terms are combined, the errors involved are compensating and, therefore, do not significantly affect the overall results.

The general equation for accumulated intake of water into a soil can be written:

$$F = aT_o^b + c \qquad \text{(Eq. 4-3)}$$

Therefore, when advance is assumed to vary linearly with time, the average depth of water that infiltrates the soil in the time (T_t) required for the advancing front to reach a point L_t feet from the head of the border strip can be obtained by integrating equation 4-3 between the limits of T_t and zero and then dividing by T_t. Thus,

$$F_a = \frac{a}{1 + b}\ T_t^{\ b} + c \qquad \text{(Eq. 4-4)}$$

The maximum and average depth of water on an impervious level border strip at any time during the advance period can be computed on a quasi-rational basis using the Manning equation:

$$Q = A\ \frac{1.486}{n}\ r^{2/3}\ s_1^{\ 1/2} \qquad \text{(Eq. 4-5)}$$

In level border flow, considering a unit-width strip, $A = d_1$ and $r = d_1$, the hydraulic slope (s_1) equals d_1/Lt. Therefore,

$$Q_u = (d_1)\frac{1.486}{n} d_1^{2/3}\left(\frac{d_1}{L_t}\right)^{1/2} = \frac{1.486}{n\ L_t\ 1/2}(d_1)^{13/6} \qquad \text{(Eq. 4-6)}$$

or

$$d_1 = \left(\frac{1}{1.486}\right)^{6/13} n^{6/13}\ Q_u^{6/13}\ L_t^{3/13} \qquad \text{(Eq. 4-7)}$$

However, the volume of water run onto the border strip is equal to the average depth of surface storage times the length of advance. Therefore,

$$L_t = \frac{60\ Q_u T_a}{d_a} \qquad \text{(Eq. 4-8)}$$

Combining equations 4-7 and 4-8

$$d_1 = \left(\frac{1}{1.486}\right)^{6/13}(60)^{3/13}\ n^{6/13}\ Q_u^{9/13}\ T_a^{3/13}\ d_a^{-3/13} \qquad \text{(Eq. 4-9)}$$

Empirical studies have shown that on an impervious level surface the average depth of flow of an advancing stream is approximately 80 percent of the maximum depth, or $d_a = 0.80\ d_1$. Substituting this value in equation 4-9:

$$(d_1)\ (d_1)^{3/13} = \left(\frac{1}{1.486}\right)^{6/13}\left(\frac{60}{0.80}\right)^{3/13} n^{6/13}\ Q_u^{9/13}\ T_a^{3/13} \qquad \text{(Eq. 4-10)}$$

or

$$d_1 = \left[\left(\frac{1}{1.486}\right)^{6/13}(75)^{3/13}\ n^{6/13}\ Q_u^{9/13}\ T_a^{3/13}\right]^{13/16}$$

$$= \left(\frac{1}{1.486}\right)^{3/8}(75)^{3/16}\ n^{3/8}\ Q_u^{9/16}\ T_a^{3/16}$$

$$= 1.94\ n^{0.3750}\ Q_u^{0.5625}\ T_a^{0.1875} \qquad \text{(Eq. 4-11)}$$

And the average depth is only 0.8 as great, or:

$$d_a = 1.55\ n^{0.3750}\ Q_u^{0.5625}\ T_a^{0.1875} \qquad \text{(Eq. 4-12)}$$

If T_t is considered to be equal to T_a and equations 4-4 and 4-12 are combined with equation 4-2, the length of advance (L_t) can be related to the time of advance (T_t) for a given soil having intake parameters (a), (b), and (c); a given stream size (Q_u); and a given roughness coefficient (n) as follows:

$$L_t = \frac{720\ Q_u\ T_t}{\left[\frac{aT_t^{\,b}}{1+b} + c + 18.6n^{\,0.3750}\ Q_u^{\,0.5625}\ T_t^{\,0.1875}\right]} \qquad \text{(Eq. 4-13)}$$

On a level border the water theoretically disappears from the entire surface at the same instant of time. Therefore, the total intake opportunity time (T_o) at any point can be estimated by adding the time required for the net irrigation to enter the soil (T_n) and the time required to cover the total length of run (T_t-total) and subtracting the time of advance to the point (T_t-point).

Figure 4-2 shows the advance curve, the intake opportunity time at each 100-foot station, and the average intake opportunity time for a 3-inch net application on a 1.0 family soil.

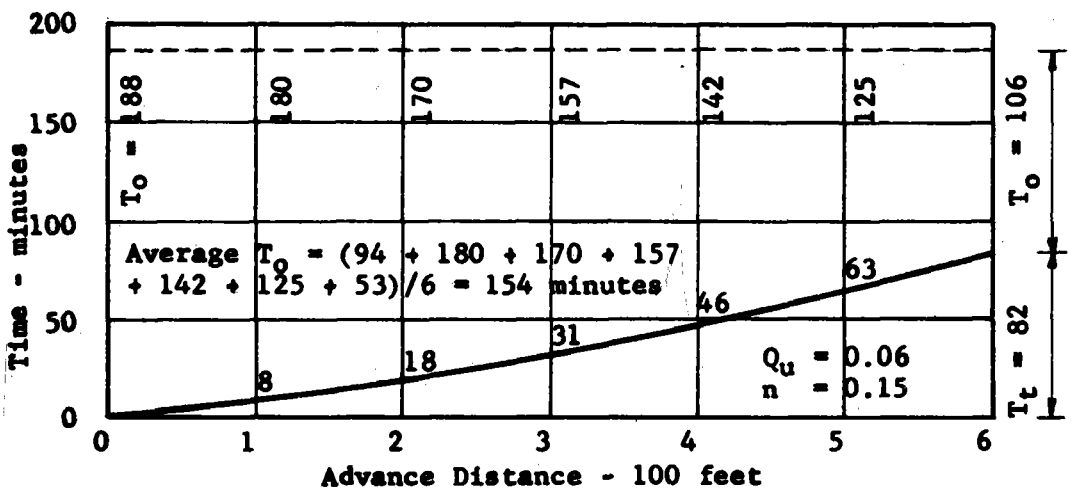


Figure 4-2.--Typical advance curve with computation of average intake opportunity time

The intake characteristics of a soil in the 1.0 family are represented by the equation $F = 0.0701\ T^{0.785} + 0.275$ (see table 4-2). If this equation is solved for the average intake opportunity time of 154 minutes, shown in figure 4-2, the average intake is 3.93 inches. This, then, is the gross average depth of water (F_g) that must be applied to get a 3-inch net depth of intake at the last point in the border strip that is covered by water.

The design efficiency (E) is 100 times the ratio of net depth of application (F_n) to gross depth of application (F_g):

$$E = \frac{100\ F_n}{F_g} \qquad \text{(Eq. 4-14)}$$

In figure 4-2, the design efficiency is 100 x 3.0/3.93 = 76 percent and the ratio of (T_t) to (T_n) is 82/106 = 0.774. Similar computations for various net depths of application and unit-width stream sizes have been made for each of the eight intake families. The computations show that design application efficiency is closely related to the ratio of T_t to T_n and can be estimated satisfactorily from the curve shown in figure 4-3.

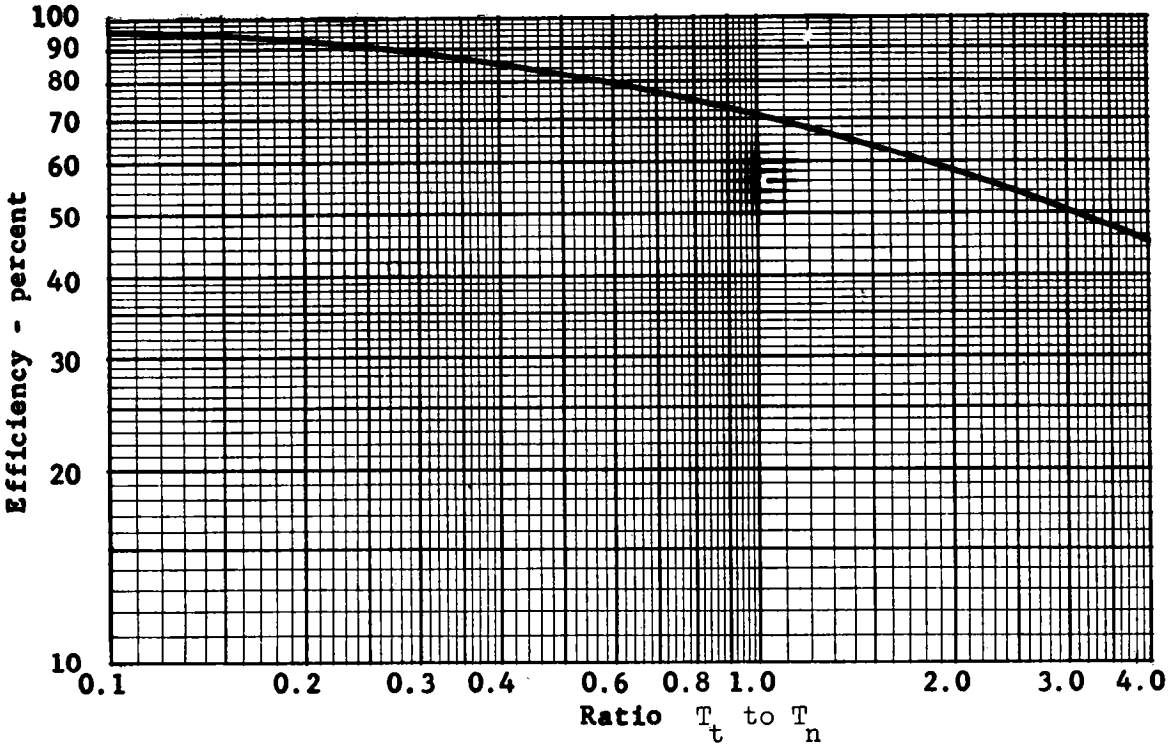


Figure 4-3.--Chart for estimating efficiency of level border irrigation

Table 4-4 has been developed from figure 4-3.

Table 4-4.--Ratio of T_t to T_n for various efficiency values

Efficiency	T_t to T_n
Percent	Ratio
95	0.16
90	.28
85	.40
80	.58
75	.80
70	1.08
65	1.45
60	1.90
55	2.45
50	3.20

If the application efficiency is known or is assumed, the gross application can be determined from the equation:

$$F_g = \frac{100\ F_n}{E} \qquad \text{(Eq. 4-15)}$$

The required time of application (T_a)--the time required to apply the gross application onto the border strip--can be computed as

$$T_a = \frac{F_g L}{720\ Q_u} \qquad \text{(Eq. 4-16)}$$

or as:

$$T_a = \frac{F_n\ L}{7.2\ Q_u\ E} \qquad \text{(Eq. 4-17)}$$

Note that the time of application may be greater or less than the time of coverage.

Design Limitations

In theory, maximum depth of flow and maximum deep percolation both occur at the point where water is introduced onto a level border strip. For any given set of site conditions, the depth of flow varies directly and the amount of deep percolation varies inversely with irrigation stream size per foot of border strip width (Q_u). Thus, if a limit is set on depth of flow, the only way to reduce deep percolation is to shorten the length of the border strip. If limits are set for both depth of flow and deep percolation, then the design limit for length is determined.

Maximum Depth of Flow.--Flow at the head end of level border strips must not exceed some practical depth related to the construction and maintenance of border ridges. Thus, an irrigation stream that can produce flow depth in excess of about 6 inches generally is inadvisable. Greater depth may be practical under special conditions, but depth of flow in excess of 8 or 10 inches seldom should be considered. Figure 4-4 can be used to estimate the depth of flow expected in level borders; it is a graphic solution of equation 4-11 with a roughness coefficient (n) of 0.15. Depth of flow associated with other values of n can be determined by multiplying the values represented in figure 4-4 by the appropriate conversion factors shown in the upper left corner of the chart.

Deep Percolation.--Since all the difference between net and gross irrigation applications is lost to deep percolation, it is desirable to limit this difference as much as possible. On many sites excess deep percolation causes acute drainage problems. To avoid this condition, the design efficiency usually should not be less than about 80 percent. Figure 4-3 shows that an 80 percent efficiency can be obtained if the time required to cover the border strip is not more than 60 percent of the time required for the net application to enter the soil. A design efficiency of less than 70 percent is considered only for soils having excellent internal drainage. On sites where irrigation water supplies are limited or costly, where subsurface drainage problems are acute, or where crops can be damaged by prolonged surface flooding, design efficiency in excess of 90 percent often is practical.

Construction Requirements

Land Leveling.--Although level borders are described and designed as flat-bottomed basins, there are reasons to justify variations in construction. First, it is difficult to construct and maintain a perfectly level land surface. Normal land leveling techniques do well to limit variations to 0.1 foot in the finished land surface. If leveling for a level border is staked as a level plane, the constructed land surface can contain low areas that are subject to excessive deep percolation or prolonged flooding that may damage crops. Also, the constructed land surface can contain reverse grades in the direction of irrigation. These reverse grades can retard the rate of advance and reduce application efficiency to considerably below design efficiency. To help avoid these conditions, fields can be staked for leveling with a slight grade in the direction of irrigation. However, the total fall in the length of the border strips cannot be more than about one-half the net depth of application used as a basis for design. No adjustment is made in the design to compensate for such slight grades.

Border furrows.--In addition to, or in lieu of, staking fields for a slight slope in the direction of irrigation, large furrows can be constructed and maintained on each side of the border ridges. The furrows help to speed rate of coverage of the border strip and to reduce depth of flow and deep percolation adjacent to the turnouts. These channels also facilitate removal of excess rainfall or irrigation water.

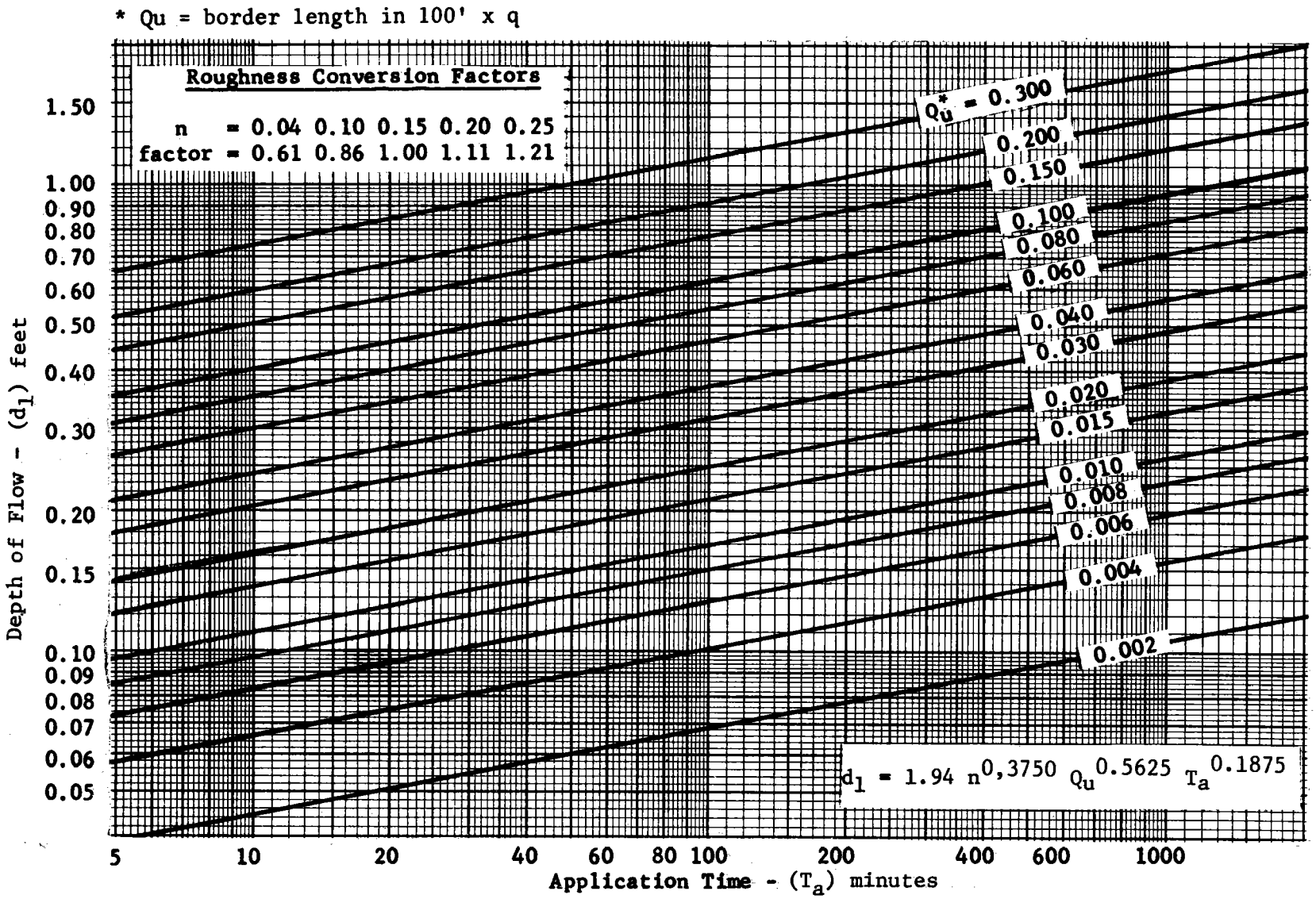


Figure 4-4.--Chart for estimating depth of flow in level borders with n of 0.15

Drainage facilities.--After an accidental overirrigation or periods of heavy rainfall, it may be necessary to drain excess water from level borders. The facilities needed are determined by how often such drainage may be needed. Surface drains usually are needed on soils of low intake rate or in areas subject to heavy summer rainstorms, or both. It is advisable to provide them for level borders on all soils in the 0.1 intake family and, in high rainfall areas, on soils in the 0.3 and 0.5 intake families. Under some circumstances they may be needed on soils of higher intake rate.

Turnouts.--Erosion on fields with level borders generally is not a problem. However, where velocity of the irrigation stream turned onto a border strip is in excess of about 3 feet per second, potholes or scour areas may develop adjacent to the turnouts. This possibility is not a limitation to design, but it does indicate a need for designing or selecting turnout structures that have a low velocity discharge rate or energy dissipation features.

Border Ridges.--Border ridges should be constructed so that crown width is at least as great as ridge height. The ridges can be built up so that they have a settled height at least equal to the greater of (1) the design gross depth of application (F_g) or (2) the design maximum depth of flow (d_1) plus 0.15 foot. If the time of application (T_a) exceeds the time of advance (T_t), the water depth on the border strip can exceed the maximum depth of flow (d_1) as computed according to equation 4-11.

Design Procedure

In preparing level border irrigation layouts, the designer must know the intake characteristics of the soil, must select a roughness coefficient value (n) that is appropriate for the crops to be irrigated, and must select the net depth of application (F_n) to be used as a basis for design. He then must determine one or more of the following:

1. Length of run that can be irrigated with a given stream size at a given efficiency.
2. Stream size needed to irrigate a given length of run at a given efficiency.
3. Maximum flow depth expected if using a given stream size and length of run that can be irrigated with that stream at a given efficiency.
4. Allowable stream size and related length of run at a given efficiency for a given maximum depth of flow.

Length of run (L) can be found for any given stream size (Q_u) and efficiency (E) by direct solution of equation 4-13. The time (T_n) required for the infiltration of the desired net application (F_n) and the constants a, b, and c can be determined from the soil intake curve. Then the allowable advance time (T_t) for any desired efficiency can be computed by multiplying T_n by the appropriate T_t to T_n ratio from figure 4-3 or table 4-4.

A similar solution for the stream size (Q_u) needed for a given length of run (L) and efficiency (E) is not possible. A trial-and-error procedure must be used.

The depth of flow expected with a given stream size (Q_u), efficiency (E), and related length of run (L) can be estimated by reference to figure 4-4. The application time (T_a) can be determined from equation 4-17.

The allowable stream size for a given maximum depth of flow (d_1) cannot be determined directly. A trial-and-error procedure must be used.

Design Charts

To simplify design procedure and eliminate trial and error solution of equations, a series of design charts have been prepared. Each chart is for a single intake family (I_F), a single roughness coefficient (n), and a single net depth of application (F_n). These charts for n values of 0.04, 0.15, and 0.25 are in appendices A, B, and C.

The design charts show relationships between the length of run, stream size, depth of flow, and time of application for any given or assumed efficiency. Figure 4-5 is a sample chart for an 0.15 n value, a 0.5 intake family, and a 3-inch net depth of application.

These charts are versatile. Almost any known or assumed value(s) can be the basis for design. If a field has border strips 750 feet long, for example, an irrigation stream of 0.071 cfs per foot of strip width is needed for 85 percent efficiency, 0.118 cfs for 90 percent efficiency, and only 0.043 cfs for 80 percent efficiency.

Based on the stream size required for 85 percent efficiency, the maximum depth of flow is 0.45 foot. If the design requirement is a maximum flow depth of 0.45 foot, the design can start at that point and the chart can be used to determine the maximum length of run and the required stream size for any desired efficiency. For the 85 percent efficiency shown in figure 4-5, the time of application is 52 minutes. With a stream of 0.043 cfs needed for an efficiency of 80 percent, the time of application is 91 minutes.

Graded Border

This is a balanced advance-and-recession kind of water application. The border strips have some slope in the direction of irrigation, and the ends usually are not closed. Each strip is irrigated by turning in a stream of water at the upper end. The stream size must be such that the desired volume of water is applied to the strip in a time equal to, or slightly less than, that needed for the soil to absorb the net amount required. When the desired volume of water has been delivered on to the strip, the stream is turned off. The water temporarily stored on the ground surface then moves on down the strip and completes the irrigation. Uniform and efficient application of water depends on the use of an irrigation stream of the proper size. Too large a stream results in

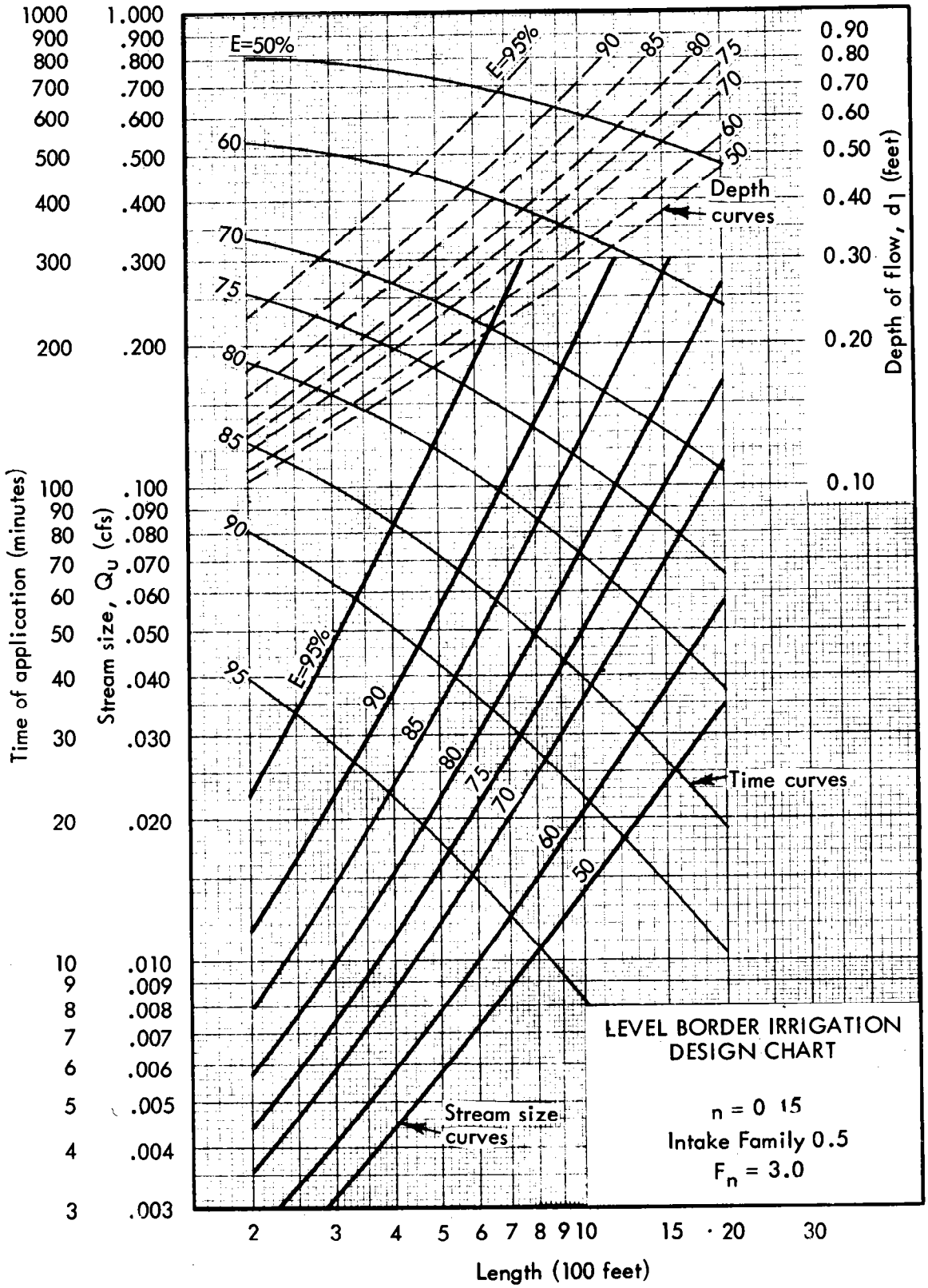


Figure 4-5.--Sample design chart for level border irrigation.

inadequate irrigation at the upper end of the strip or in excessive surface runoff at the lower end. If the stream is too small, the lower end of the strip is inadequately irrigated or the upper end has excessive deep percolation.

Adaptability

This kind of irrigation is suitable for all close-growing, noncultivated, sown or drilled crops, except rice and other crops grown in ponded water. Legumes, grasses, small grains, and mint are commonly irrigated by this method. It also is used to irrigate orchards and vineyards.

Graded border irrigation can be used on most soils. It is, however, best suited to soils with a moderately low to a moderately high intake rate (0.5 through 3.0 intake families). It is seldom used on coarse sandy soils of extremely high intake rate because of design limitations. Also, it is not well suited for use on soils of extremely low intake rate since, to provide adequate intake time without excessive surface runoff, the irrigating stream may be too small to cover the border strip completely.

Graded border irrigation is best suited to slopes of less than 0.5 percent. It can be used successfully on steeper slopes in areas where erosion from rainfall is not a hazard if the soil intake rate is not too low. For nonsodforming crops, this method is seldom used on slopes steeper than 2 percent. It can be used on slopes of 4 percent or steeper for the irrigation of sod crops if climatic conditions or supplementary irrigation methods can be depended on to establish good crop stands. On steeper slopes, border strips must be leveled carefully and all cross slope eliminated.

Advantages

Field application efficiency is good to excellent if the border strips are designed and installed properly and water management practices are followed. Labor requirements are low, and border strip dimensions can be designed for efficient operation of tilling, planting, and harvesting machinery. Within broad limits, border strips can be designed for irrigation grades that minimize land leveling costs. In areas where surface drainage is critical, graded borders provide an excellent means for removing excess surface water rapidly.

Limitations

The use of graded borders is limited by the need for (1) complete elimination of cross slope where soil intake characteristics or irrigation grades or both require small irrigating streams; (2) topography that is relatively smooth or soils that are deep enough to permit adequate leveling; and (3) considerable skill in irrigating, and skilled irrigators who often are not readily available.

Design Assumptions

The hydraulic characteristics of graded border irrigation are not completely known. Therefore, it is not possible to develop a completely

rational design procedure until these characteristics have been more adequately determined. If certain empirical hydraulic relationships are assumed valid, however, a rational or quasi-rational design in accord with relationships between soil intake, stream size, border area, and application depth can be developed.

On sites suitable for graded border irrigation, advance-and-recession curves will be reasonably well balanced and the area irrigated satisfactorily if these two conditions are met:

1. The volume of water delivered to the border strip is adequate to cover it to an average depth equal to the gross irrigation application.
2. The intake opportunity time at the head of the border is equal to the time necessary for the soil to absorb the net irrigation.

The first condition refers to the gross application; the second condition depends on the net application. The ratio between the net and the gross applications (field efficiency) must be estimated for conditions of the site under consideration. Also the proposed design procedure must be restricted to sites suitable for graded border irrigation. Empirical limits of site adaptation and guide information on design efficiency are given in table 4-12 on page 4-33.

Design Equations

The volume of water (V) needed to cover a border strip 1 foot wide to an average depth equal to the gross depth of application (F_g) and to satisfy the first condition can be stated as follows:

$$V = \frac{LF_g}{12} \qquad \text{(Eq. 4-18)}$$

where

$$F_g = \frac{100F_n}{E} \qquad \text{(Eq. 4-19)}$$

Therefore,

$$V = \frac{100LF_n}{12E} \qquad \text{(Eq. 4-20)}$$

Recession does not start immediately after the desired volume of water has been introduced to the head of the border strip. The time from the moment inflow is shut off until the impounded water has drained away from the head of the strip is known as the recession-lag time (T_L). For the intake opportunity time (T_o) to equal the time required for the soil to absorb the net irrigation (T_n) at the head of the strip, the time required to introduce the necessary volume of water is equal to (T_n) minus T_L. Therefore, to satisfy the second condition:

$$V = Q_u\ (T_n - T_L)\ 60 \qquad \text{(Eq. 4-21)}$$

Equating volumes for both conditions:

$$\frac{100LF_n}{12E} = 60\ Q_u\ (T_n - T_L) \qquad \text{(Eq. 4-22)}$$

So

$$L = 7.2Q_u\ (T_n - T_L)\ E/F_n \qquad \text{(Eq. 4-23a)}$$

or

$$Q_u = \frac{LF_n}{7.2\ (T_n - T_L)E} \qquad \text{(Eq. 4-23b)}$$

In equation 4-23b, the factors L and F_n usually are given. T_n, the time required for infiltration of the net depth of application (F_n), can be determined if the intake characteristics of the soil in the design area are known. However, approximating methods or estimates must be used to establish the values of T_L and E. The values of these factors may be estimated using figure 4-7 for lag time and table 4-12 for efficiency.

Relationship to Unit Stream Concept

The concept of a unit stream in border irrigation design was introduced about 1956. At that time, a unit stream was defined as the stream required for each 100 feet of border strip 1 foot wide (q). The basic assumption of this concept is that irrigation stream size is directly proportional to border strip area. Under this assumption--once the proper unit stream is determined for a given slope, soil, and depth of application--the actual irrigating stream for any set of border strip dimensions is merely the product of the unit stream and the number of unit areas in the strip.

The unit stream concept still seems valid. But the theoretical unit stream needed to satisfy intake requirements must be increased to compensate for lag in the start of recession. This increase is greatest on very gentle slopes and generally has no practical significance on slopes over 0.4 percent. If the unit stream (q) is considered as the flow that supplies an average depth of F_n inches to an area 1 foot wide and 100 feet long in time T_n, the unit stream can be computed as:

$$q = \frac{F_n}{7.2T_n} \qquad \text{(Eq. 4-24)}$$

The irrigation stream required per foot of border strip width then can be considered as:

$$Q_u = Kq \left[\frac{L}{100}\right] \left[\frac{100}{E}\right] \qquad \text{(Eq. 4-25)}$$

By comparing equations 4-23b and 4-25, it can be seen that the site factor (K) is the ratio of the required intake opportunity time to the required irrigation application time.

$$K = \frac{T_n}{T_n - T_L} \qquad \text{(Eq. 4-26)}$$

Recession-Lag Time

If, in equations 4-24, 25, and 26, the values of T_n and T_L are known or can be approximated, the relationship between L and Q_u can be determined for any assumed value of E. The intake time (T_n) corresponding to the required net depth of application (F_n) can be taken directly from the design intake curve for the site. The recession-lag time (T_L) can be considered as the time required to drain the water stored above the elevation of the upper end of the border strip at a rate equal to the just terminated rate of application.

As shown in figure 4-6, the recession volume (lined triangular area) can be computed:

$$\text{Recession volume} = (d_1/2)\ (d_1/s_1) = d_1^2/2s_1 \qquad \text{(Eq. 4-27)}$$

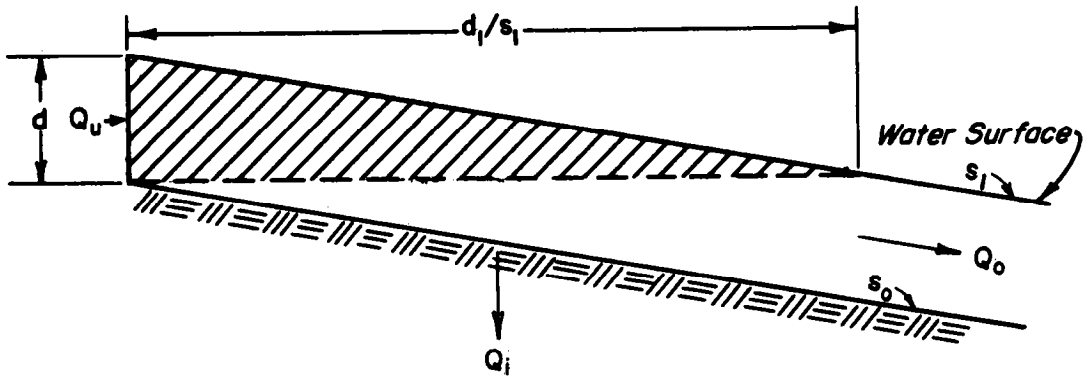


Figure 4-6.--Diagram of recession-lag time

If it is assumed that, within the recession-lag time, the depth of flow at the lower end of the reach (d_1/s_1) remains virtually unchanged, the flow (Q_o) moving downstream then remains unchanged. The intake rate (Q_i) also can be expected to remain nearly constant during the recession-lag period. Therefore, it also can be assumed that the total outflow draining the recession volume is Q_i plus Q_o, or Q_u. The recession-lag time can be computed as:

$$T_L = \frac{d_1^2/2s_1}{60\ Q_u} = \frac{d_1^2}{120\ Q_u s_1} \qquad \text{(Eq. 4-28)}$$

Flow at Normal Depth.--Assuming that water flows at normal depth in the border strip, i.e., $s_o = s_1$, the depth d_n is related to Q_u and slope as indicated by the Manning formula:

$$d_n = \frac{Q_u^{0.6}}{(1.486/n)^{0.6}\ s_o^{\ 0.3}} \qquad \text{(Eq. 4-29)}$$

Also, if equation 4-29 is combined with equation 4-28, the recession-lag time can be related to Q_u, s_o, and n as follows:

$$T_L = \frac{Q_u^{0.2}}{120(1.486/n)^{1.2}\ s_o^{\ 1.6}} \qquad \text{(Eq. 4-30)}$$

Figure 4-7 is a graphic solution of equations 4-29 and 4-30 when the Manning roughness coefficient (n) equals 0.15. Depth of flow and recession-lag time associated with other values of n can be determined by multiplying the values in figure 4-7 by the appropriate conversion factors in table 4-5.

Table 4-5.--Conversion factors for depth of flow and recession-lag time for various roughness coefficients

Roughness coefficient (n)	Flow depth (C_d)	Recession-lag time (C_t)
0.02	0.30	0.04
.04	.45	.21
.06	.58	.33
.08	.69	.47
.10	.79	.62
.15	1.00	1.00
.20	1.18	1.42
.25	1.35	1.85

On steep slopes flow approaches normal depth at the upper end of the border strip within a relatively short advance period. On more gentle slopes, however, flow may not reach normal depth within the required irrigating period. The recession-lag times and depths shown in figure 4-7, therefore, represent maximum values.

Flow at Less Than Normal Depth.--Estimates of flow depth and recession-lag time for low-gradient borders--where flow may not reach normal depth--are made by developing approximate water surface profiles for advancing streams. For developing these profiles, it is practical to assume that at any instant the friction slope in the Manning equation is equal to the irrigation slope, plus the depth of flow at the upper end

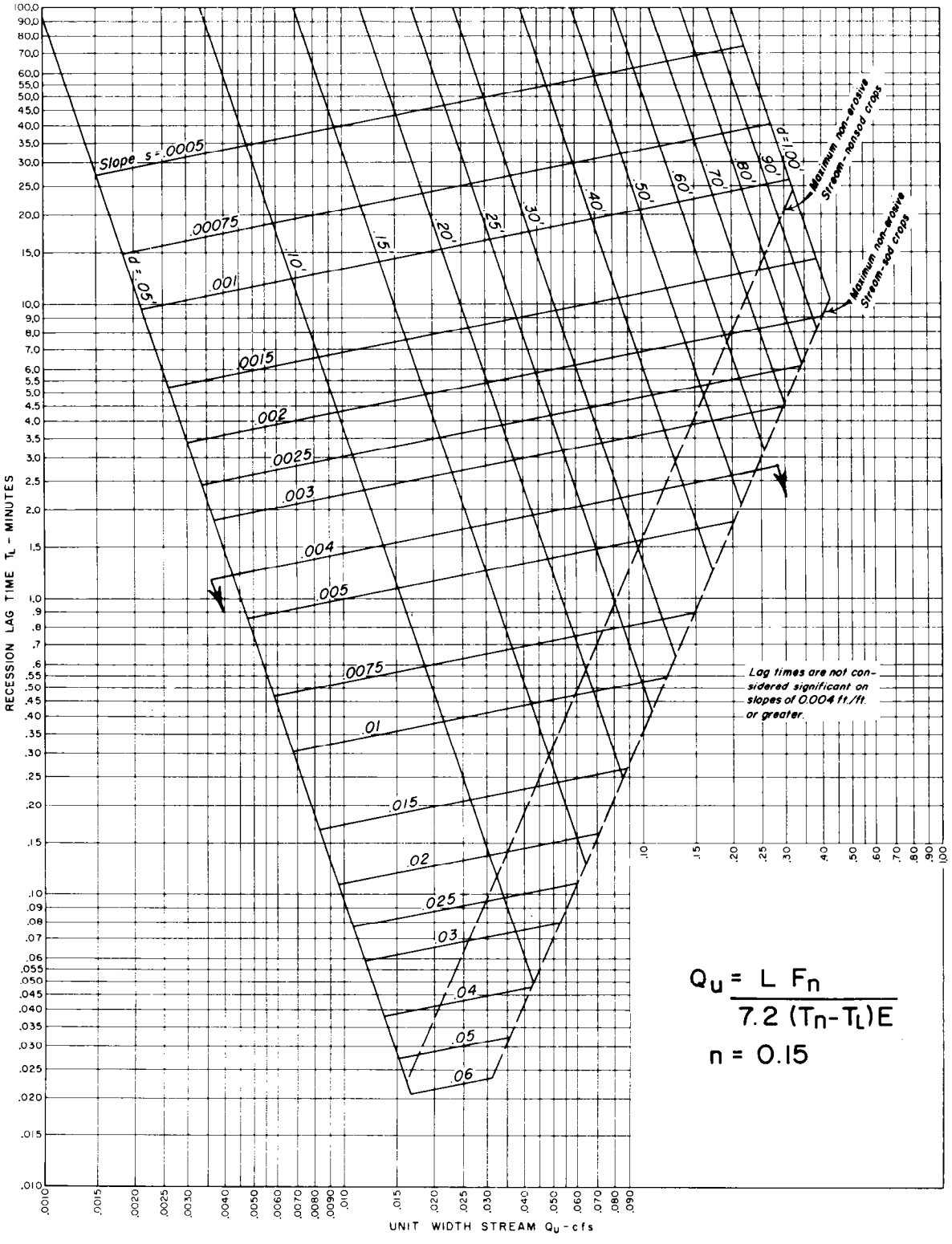


Figure 4-7.--Depth of flow and recession-lag time in graded border irrigation

of the border strip divided by the distance the stream has advanced up to that particular instant. Thus,

$$s_1 = s_o + d_1/L_t \qquad \text{(Eq. 4-31)}$$

and

$$d_1 = \frac{Q_u^{0.6}}{(1.486/n)^{0.6}(s_o + d_1/L_t)^{0.3}} \qquad \text{(Eq. 4-32)}$$

The water surface profiles for given values of stream size (Q_u), irrigation slope (s_o), and roughness coefficient (n) are developed by assuming a series of hydraulic slopes (s_1) and computing d_1, d_1/L_t, and L_t as illustrated in sample calculation 4-1. The profiles then can be related to time by summing the $(\Delta L_t)d_a$ values to obtain volume and dividing volume by the rate of application to obtain related time of application:

$$T_a = \frac{\Sigma[(\Delta L_t)d_a]}{60\ Q_u} \qquad \text{(Eq. 4-33)}$$

The recession-lag time corresponding to each assumed hydraulic slope value (s_1) can be computed using equation 4-28. The recession-lag time value then can be plotted against the intake opportunity time (T_o) and tabulated to provide a means of estimating T_L for any given border strip slope, unit-width stream, and required intake opportunity time. Table 4-6 is a design table developed for roughness coefficients (n) of 0.04, 0.15, and 0.25.

The depth of flow to be expected at the upper end of a low-gradient border strip can be estimated for any given unit-width stream and required intake opportunity time (see table 4-7). The normal depths of flow and recession-lag times shown in figure 4-7 can be used as a basis for designing border strips on slopes over 0.4 percent (0.004 feet per foot) without introducing any appreciable error (see tables 4-6 and 4-7). In fact, for the steeper slopes the recession-lag time is so short it has little practical significance.

Design Limitations

Nonerosive Streams.--The streams used in graded border irrigation must be nonerosive. To protect the upper end of the border strip against erosion, the irrigation stream per foot of strip width (Q_u) must not exceed the following empirical criteria:

For nonsodforming crops such as alfalfa and small grains:

$$Q_u \max = 0.0019\ s_o^{-0.75} \qquad \text{(Eq. 4-34)}$$

For well-established, dense sod crops:

$$Q_u \max = 0.0038\ s_o^{-0.75} \qquad \text{(Eq. 4-35)}$$

Sample calculation 4-1.--Depth of flow and recession-lag time as related to required intake opportunity time

[Assume $Q_u = 0.100$; $S_o = 0.002$; and $n = 0.150$]

S_1	$S_1^{0.3}$	d_1	$d_1/L_t = S_1 - S_o$	L_t	ΔL_t	d_a	$(\Delta L_t)\ d_a$	$\Sigma\ (\Delta L_t)\ d_a$	T_a	T_L	$T_o = T_a + T_L$
.1000	.501	.1266	.0980	1.292	1.292	.0633	0.082	0.082	0.01		
.0900	.485	.1308	.0880	1.486	0.194	.1287	0.025	0.107	0.02		
.0800	.469	.1353	.0780	1.735	0.249	.1331	0.033	0.140	0.02		
.0700	.450	.1410	.0680	2.074	0.339	.1382	0.047	0.187	0.03		
.0600	.430	.1476	.0580	2.545	0.471	.1443	0.068	0.255	0.04		
.0500	.406	.1563	.0480	3.256	0.711	.1520	0.108	0.363	0.06		
.0400	.380	.1670	.0380	4.395	1.139	.1617	0.184	0.547	0.09		
.0300	.350	.1813	.0280	6.475	2.080	.1742	0.362	0.909	0.15		
.0200	.309	.2053	.0180	11.406	4.931	.1933	0.953	1.862	0.31		
.0100	.251	.2528	.0080	31.600	20.194	.2291	4.626	6.488	1.08	0.53	1.61
.0090	.244	.2600	.0070	37.143	5.543	.2564	1.421	7.909	1.32	0.63	1.95
.0080	.235	.2700	.0060	45.000	7.857	.2650	2.082	9.991	1.67	0.76	2.43
.0070	.225	.2820	.0050	56.400	11.400	.2760	3.146	13.137	2.19	0.95	3.14
.0060	.215	.2951	.0040	73.775	17.375	.2886	5.014	18.151	3.03	1.21	4.24
.0050	.204	.3110	.0030	103.667	29.892	.3031	9.060	27.211	4.54	1.61	6.15
.0040	.191	.3322	.0020	166.100	62.433	.3216	20.078	47.289	7.88	2.30	10.18
.0030	.175	.3626	.0010	362.600	196.500	.3474	68.264	115.553	19.26	3.65	22.91
.0025	.166	.3822	.0005	764.400	401.800	.3724	149.630	265.183	44.20	4.87	49.07
.0024	.164	.3869	.0004	967.250	202.850	.3846	78.016	343.199	57.20	5.20	62.40
.0023	.162	.3917	.0003	1,305.667	338.417	.3893	131.746	474.945	79.16	5.56	84.72
.0022	.160	.3966	.0002	1,983.000	677.333	.3942	267.005	741.950	123.66	5.96	129.62
.0021	.157	.4041	.0001	4,041.000	2,058.000	.4004	824.023	1,565.973	261.00	6.48	267.48
.0020	.155	.4094	(Normal depth)							6.98	

Table 4-6.--Recession-lag time in low-gradient borders

Oppor. Time T_o	s_o = 0.0005				s_o = 0.001				s_o = 0.002				s_o = 0.004			
	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200
						Recession-Lag Time in Minutes for n = 0.04										
min.																
10	2.0	2.4	2.8	3.1	1.1	1.5	1.9	2.0			1.0	1.1				
30	3.4	4.5	5.6	6.0	1.4	2.1	3.0	3.3			1.2	1.4				
60	4.1	5.8	7.9	8.5	1.5	2.4	3.5	3.9			1.3	1.5				
100	4.5	6.6	9.4	10.3	1.6	2.5	3.8	4.2			1.4	1.6				
200	4.8	7.3	10.8	12.2	1.6	2.5	4.1	4.6			1.4	1.6	Note: Recession-lag times of less than one minute are omitted			
400	5.0	7.8	11.8	13.5	1.6	2.5	4.2	4.7			1.4	1.6				
600	5.0	7.9	12.2	14.0	1.6	2.5	4.2	4.8			1.4	1.6				
800	5.0	8.0	12.4	14.3	1.6	2.5	4.2	4.8			1.4	1.6				
1000	5.0	8.0	12.6	14.5	1.6	2.5	4.2	4.8			1.4	1.6				
2000	5.0	8.0	12.8	14.7	1.6	2.5	4.2	4.8			1.4	1.6				
						Recession-Lag Time in Minutes for n = 0.15										
min.																
10	3.2	3.3	3.4	3.4	2.4	2.7	3.0	3.1	1.5	1.9	2.2	2.4		1.0	1.4	1.5
30	7.3	8.2	8.9	9.2	4.6	5.7	6.8	7.1	2.1	3.0	4.1	4.5		1.3	1.9	2.1
60	11.3	13.6	15.5	16.3	5.9	8.1	10.3	10.9	2.4	3.6	5.2	5.7		1.4	2.1	2.3
100	14.5	18.4	22.1	23.3	6.6	9.6	13.0	14.0	2.6	3.9	5.7	6.4		1.4	2.2	2.4
200	18.4	25.3	33.0	35.0	7.4	10.9	16.1	17.7	2.7	4.2	6.3	7.2		1.5	2.3	2.6
400	21.2	30.7	43.3	47.5	8.0	11.8	18.1	20.4	2.8	4.3	6.7	7.6		1.5	2.3	2.6
600	22.4	33.4	48.5	53.5	8.2	12.3	19.0	21.7	2.8	4.4	6.8	7.8		1.5	2.3	2.6
800	23.0	35.0	51.3	57.3	8.2	12.5	19.6	22.3	2.8	4.4	6.9	7.9		1.5	2.3	2.7
1000	23.5	36.0	53.5	60.0	8.3	12.7	20.0	23.0	2.8	4.4	7.0	8.0		1.5	2.3	2.7
2000	24.7	38.0	58.0	66.0	8.4	13.0	20.7	23.7	2.8	4.4	7.0	8.0		1.5	2.3	2.7
						Recession-Lag Time in Minutes for n = 0.25										
min.																
10	3.2	3.4	3.5	3.5	2.7	3.0	3.1	3.3	2.0	2.4	2.8	2.8	1.1	1.5	1.8	2.0
30	8.3	9.2	9.7	9.9	6.1	7.1	8.0	8.3	3.4	4.5	5.7	6.0	1.4	2.1	3.0	3.3
60	14.4	16.2	17.6	18.2	8.8	11.0	13.3	14.1	4.0	5.7	7.8	8.5	1.5	2.3	3.5	3.9
100	20.7	23.4	26.5	27.4	10.6	14.2	18.0	19.3	4.4	6.4	9.2	10.2	1.6	2.5	3.7	4.2
200	29.4	35.7	43.0	45.0	12.4	17.9	24.1	26.8	4.7	7.2	10.7	12.0	1.7	2.6	4.0	4.6
400	37.0	48.5	63.0	67.0	13.8	20.5	29.3	33.4	4.9	7.6	11.7	13.2	1.7	2.7	4.1	4.7
600	40.8	54.5	74.5	81.0	14.5	21.6	32.0	36.3	5.0	7.8	12.2	13.7	1.7	2.7	4.1	4.8
800	42.0	58.0	82.0	90.0	14.8	22.0	33.7	38.0	5.0	7.9	12.4	14.0	1.7	2.7	4.1	4.8
1000	44.0	61.0	87.5	96.0	15.0	22.4	34.7	39.3	5.0	8.0	12.5	14.1	1.7	2.7	4.1	4.8
2000	45.5	68.0	99.0	110.0	15.6	23.0	36.7	41.0	5.0	8.0	12.8	14.5	1.7	2.7	4.1	4.8

Table 4-7.--Depth of flow in low-gradient borders

Oppor. Time T_o	s_o = 0.0005				s_o = 0.001				s_o = 0.002				s_o = 0.004			
	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200	Q_u 0.001	Q_u 0.010	Q_u 0.100	Q_u 0.200
							Depth of Flow in Feet when n = 0.04									
min.																
10	0.01	0.06	0.20	0.29	0.01	0.05	0.19	0.29	0.01	0.04	0.17	0.26	0.01	0.04	0.14	0.22
30	0.02	0.06	0.24	0.36	0.01	0.05	0.21	0.32	0.01	0.05	0.18	0.27	0.01	0.04	0.15	0.23
60	0.02	0.07	0.25	0.38	0.01	0.06	0.22	0.33	0.01	0.05	0.18	0.28	0.01	0.04	0.15	0.23
100	0.02	0.07	0.26	0.40	0.01	0.06	0.22	0.34	0.01	0.05	0.18	0.28	0.01	0.04	0.15	0.23
200	0.02	0.07	0.27	0.41	0.01	0.06	0.22	0.34	0.01	0.05	0.19	0.29	0.01	0.04	0.15	0.23
400	0.02	0.07	0.27	0.42	0.01	0.06	0.22	0.34	0.01	0.05	0.19	0.29	0.01	0.04	0.15	0.23
600	0.02	0.07	0.28	0.42	0.01	0.06	0.22	0.34	0.01	0.05	0.19	0.29	0.01	0.04	0.15	0.23
800	0.02	0.07	0.28	0.42	0.01	0.06	0.22	0.34	0.01	0.05	0.19	0.29	0.01	0.04	0.15	0.23
1000*	0.02	0.07	0.28	0.42	0.01	0.06	0.22	0.34	0.01	0.05	0.19	0.29	0.01	0.04	0.15	0.23
							Depth of Flow in Feet when n = 0.15									
min.																
10	0.02	0.09	0.36	0.53	0.02	0.09	0.34	0.52	0.02	0.09	0.33	0.49	0.02	0.08	0.30	0.45
30	0.03	0.12	0.43	0.64	0.03	0.11	0.41	0.60	0.02	0.10	0.37	0.56	0.02	0.08	0.32	0.48
60	0.03	0.13	0.47	0.71	0.03	0.12	0.44	0.66	0.02	0.10	0.38	0.58	0.02	0.08	0.32	0.49
100	0.04	0.14	0.51	0.76	0.03	0.12	0.46	0.68	0.03	0.10	0.39	0.60	0.02	0.08	0.33	0.50
200	0.04	0.14	0.55	0.81	0.03	0.12	0.47	0.72	0.03	0.10	0.40	0.61	0.02	0.08	0.33	0.50
400	0.04	0.15	0.58	0.86	0.03	0.12	0.48	0.73	0.03	0.10	0.40	0.62	0.02	0.08	0.33	0.50
600	0.04	0.15	0.59	0.88	0.03	0.12	0.49	0.74	0.03	0.10	0.41	0.62	0.02	0.08	0.33	0.50
800	0.04	0.15	0.60	0.89	0.03	0.12	0.49	0.74	0.03	0.10	0.41	0.62	0.02	0.08	0.33	0.50
1000*	0.04	0.16	0.60	0.90	0.03	0.13	0.50	0.75	0.03	0.10	0.41	0.62	0.02	0.08	0.33	0.50
							Depth of Flow in Feet when n = 0.25									
min.																
10	0.03	0.12	0.43	0.64	0.03	0.12	0.42	0.64	0.03	0.11	0.42	0.61	0.03	0.10	0.39	0.58
30	0.04	0.14	0.52	0.78	0.04	0.14	0.50	0.75	0.03	0.12	0.48	0.71	0.03	0.11	0.42	0.64
60	0.04	0.16	0.58	0.87	0.04	0.15	0.56	0.83	0.03	0.13	0.50	0.76	0.03	0.11	0.43	0.66
100	0.04	0.17	0.64	0.94	0.04	0.15	0.59	0.88	0.03	0.13	0.52	0.78	0.03	0.11	0.44	0.67
200	0.05	0.18	0.70	1.04	0.04	0.16	0.63	0.94	0.03	0.14	0.54	0.80	0.03	0.11	0.44	0.67
400	0.05	0.19	0.75	1.10	0.04	0.17	0.65	0.98	0.04	0.14	0.55	0.82	0.03	0.11	0.45	0.68
600	0.05	0.20	0.77	1.10	0.04	0.17	0.66	0.99	0.04	0.14	0.56	0.83	0.03	0.11	0.45	0.68
800	0.05	0.20	0.78	1.10	0.04	0.17	0.66	1.00	0.04	0.14	0.56	0.84	0.03	0.11	0.45	0.68
1000*	0.05	0.20	0.80	1.10	0.04	0.17	0.66	1.00	0.04	0.14	0.57	0.84	0.03	0.11	0.45	0.68

* Approximately normal flow depth at 1000 minutes

Table 4-8 gives the maximum nonerosive stream size for both sod and nonsodforming crops on various slopes. Figure 4-7 shows erosion limits for these crops.

Either turnouts that control flow onto the border strips must be designed to have a low-velocity discharge rate or energy dissipators must be used to prevent excessive scouring at the upper ends of the border strips. Turnout discharge velocity should be less than 3 feet per second.

Table 4-8.--Maximum value of Q_u for nonsod and sod crops by slope

Slope	Crops	
	Nonsod	Sod
Feet per feet	Cubic feet per second	
0.0005	0.567	1.113
.0010	.337	.674
.0020	.200	.400
.0030	.148	.296
.0040	.119	.238
.0050	.101	.202
.0075	.075	.149
.0100	.060	.120
.0150	.044	.089
.0200	.036	.072
.0250	.030	.060
.0300	.026	.053
.0400	.021	.042
.0500	.018	.036
.0600	.016	.031

Maximum Depth of Flow.--The flow at the head end of the border strip must not exceed some practical depth related to the construction and maintenance of border ridges. Therefore, an irrigation stream that is expected to produce a flow depth in excess of about 6 inches generally is inadvisable. Greater depth is practical on some soils, but depth of flow in excess of 8 or 10 inches should seldom be considered. The allowable stream (Q_u) per foot of border strip width for a given maximum depth of flow in low-gradient borders can be determined from table 4-9. This table was developed from computations of water surface profiles using n values of 0.04, 0.15, and 0.25. For border strips on slopes steeper than 0.4 percent, the allowable stream size can be determined from figure 4-7 and table 4-5.

Minimum Depth of Flow.-- The irrigating stream must be large enough so that the water spreads over the entire border strip. A larger stream is needed on rough strips than is required on adequately graded and smoothed

Table 4-9.--Allowable unit-width irrigation stream for given maximum depth of flow

Slope	Flow Depth	n = 0.04 Intake Opportunity Time - minutes						n = 0.15 Intake Opportunity Time - minutes						n = 0.25 Intake Opportunity Time - minutes					
		10	30	60	100	300	600	10	30	60	100	300	600	10	30	60	100	300	600
ft./ft.	feet	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs
0.0005	0.1	.030	.022	.021	.020	.019	.018	.011	.008	.007	.006	.005	.005	.007	.006	.005	.004	.003	.003
	0.2	.100	.073	.067	.064	.060	.058	.036	.026	.022	.020	.017	.016	.025	.018	.015	.013	.011	.010
	0.3	.205	.147	.133	.128	.117	.113	.073	.054	.045	.040	.035	.032	.052	.038	.031	.027	.022	.020
	0.4	.340	.240	.217	.208	.190	.183	.120	.089	.075	.066	.056	.052	.086	.062	.051	.045	.036	.033
	0.5		.350	.316	.303	.275	.265	.178	.132	.110	.097	.083	.077	.128	.092	.076	.066	.053	.048
	0.6					.370	.357	.247	.183	.152	.133	.113	.105	.177	.127	.105	.091	.072	.065
	0.7							.320	.240	.200	.174	.146	.136	.235	.165	.137	.118	.094	.086
	0.8								.298	.250	.220	.185	.170	.298	.208	.173	.150	.118	.107
0.001	0.1	.032	.028	.027	.027	.027	.027	.011	.009	.008	.008	.007	.007	.008	.006	.005	.005	.004	.004
	0.2	.107	.091	.086	.086	.085	.084	.038	.029	.026	.024	.023	.022	.026	.020	.017	.016	.014	.013
	0.3	.215	.179	.170	.168	.166	.165	.079	.059	.052	.049	.045	.043	.053	.040	.034	.031	.028	.027
	0.4	.353	.292	.275	.272	.269	.267	.130	.096	.085	.079	.073	.070	.088	.067	.056	.052	.045	.043
	0.5			.397	.392	.388	.386	.195	.143	.125	.116	.106	.102	.130	.098	.083	.076	.066	.063
	0.6							.270	.198	.173	.159	.145	.139	.180	.135	.113	.103	.089	.086
	0.7							.345	.256	.224	.208	.189	.179	.237	.177	.148	.135	.117	.112
	0.8								.320	.280	.260	.236	.225	.300	.223	.187	.171	.146	.138
0.002	0.1	.041	.038	.036	.035	.035	.035	.012	.011	.010	.010	.010	.009	.008	.007	.006	.006	.006	.006
	0.2	.129	.120	.116	.112	.110	.109	.042	.035	.033	.032	.031	.030	.028	.023	.021	.020	.019	.018
	0.3	.255	.235	.228	.221	.218	.214	.085	.069	.065	.062	.061	.060	.057	.045	.042	.040	.037	.036
	0.4	.410	.380	.368	.360	.352	.345	.140	.113	.107	.102	.099	.097	.092	.075	.068	.065	.060	.058
	0.5							.220	.165	.155	.148	.145	.142	.138	.109	.100	.094	.088	.084
	0.6							.282	.225	.210	.200	.197	.193	.190	.150	.135	.128	.118	.113
	0.7							.370	.287	.271	.258	.255	.248	.250	.195	.176	.167	.154	.147
	0.8								.353	.340	.324	.310	.303	.315	.245	.222	.210	.198	.183
0.004	0.1	.054	.052	.052	.051	.051	.050	.015	.015	.014	.014	.014	.014	.009	.009	.009	.008	.008	.008
	0.2	.171	.163	.162	.160	.160	.160	.050	.046	.045	.045	.044	.043	.032	.029	.028	.027	.027	.026
	0.3	.338	.323	.320	.318	.316	.314	.100	.091	.088	.085	.085	.084	.064	.057	.055	.053	.052	.050
	0.4							.165	.148	.141	.138	.137	.135	.105	.092	.089	.086	.084	.082
	0.5	Note:						.240	.218	.207	.202	.200	.198	.155	.134	.130	.125	.122	.118
	0.6	For T_o > 600 minutes, determine						.323	.293	.288	.280	.274	.265	.214	.182	.177	.169	.165	.161
	0.7	Q_u from Figure 4-7							.380	.373	.363	.356	.347	.280	.236	.228	.220	.216	.210
	0.8													.357	.297	.285	.275	.267	.262

strips. The irrigation stream per foot of strip width should be no less than is computed by equation 4-36:

$$Q_u = 0.000064\ L\ s_o^{0.5}/n \qquad \text{(Eq. 4-36)}$$

Table 4-10 shows the minimum value of Q_u/L for various slopes and n values.

Table 4-10.--Minimum value of Q_u/L for various n values by slope

Slope	n = 0.04	n = 0.15	n = 0.25
Feet per foot		Cubic feet per second	
0.0005	0.00003578	0.00000954	0.00000572
.0010	.00005060	.00001349	.00000810
.0020	.00007155	.00001908	.00001145
.0030	.00008763	.00002337	.00001402
.0040	.00010120	.00002699	.00001619
.0050	.00011313	.00003017	.00001810
.0075	.00013855	.00003695	.00002217
.0100	.00016000	.00004267	.00002560
.0150	.00019600	.00005227	.00003136
.0200	.00022625	.00006033	.00003620
.0250	.00025295	.00006745	.00004047
.0300	.00027713	.00007390	.00004434
.0400	.00032000	.00008533	.00005120
.0500	.00035775	.00009540	.00005724
.0600	.00039185	.00010449	.00006270

Maximum Slope.--If equations 4-36 and 4-23b are combined, the maximum allowable slope for a given net depth of application can be determined for any given intake family and desired application efficiency.

$$0.000064\ s^{0.5}/n = Fn/7.2\ (T_n - T_L)\ E \qquad \text{(Eq. 4-37)}$$

or

$$s = \left[\frac{(n)}{0.0004608E}\ \frac{(F_n)}{T_n - T_L}\right]^2 \qquad \text{(Eq. 4-38)}$$

In using equation 4-38, the recession-lag time (T_L) can be ignored safely. The maximum slope found by the equation is based solely on the criteria for minimum depth of flow. In areas subject to erosion from rains of high intensity, that slope may be much too steep. Also, even

Table 4-11.--Maximum slopes for graded border irrigation as limited by minimum depth of flow requirements or by a minimum border length of 100 feet

Intake Family	Appl. Depth	n = 0.04 Efficiency - percent						n = 0.15 Efficiency - percent						n = 0.25 Efficiency - percent					
		50	55	60	65	70	75	50	55	60	65	70	75	50	55	60	65	70	75
	in.	Feet per foot						Feet per foot						Feet per foot					
0.3	1	.001*	.001*	.001*	.001*			.011*	.009*	.008*	.006*			.030*	.025*	.021*	.018*		
	2	#	#	#	#			.004*	.003*	.003*	.002*			.011*	.009*	.008*	.006*		
	3	#	#	#	#	#		.003*	.002*	.002*	.002*	.001*		.007*	.006*	.005*	.004*	.004*	
	4	#	#	#	#	#		.002*	.002*	.001*	.001*	.001*		.005*	.004*	.004*	.003*	.003*	
0.5	1	.002*	.002*	.001*	.001*			.030*	.025*	.021*	.018*			.083*	.069*	.058*	.049*		
	2	.001*	.001*	.001*	.001*			.012*	.010*	.008*	.007*			.033*	.027*	.023*	.020*		
	3	.001*	.001*	#	#	#		.008*	.007*	.006*	.005*	.004*		.023*	.019*	.016*	.013*	.011*	
	4	#	#	#	#	#		.006*	.005*	.004*	.004*	.003*		.018*	.014*	.012*	.010*	.009*	
	5	#	#	#	#	#		.005*	.004*	.004*	.003*	.003*		.015*	.012*	.010*	.009*	.007*	
1.0	1	.008*	.006*	.005*	.005*	.004*	.003*	.069	.078	.077*	.065*	.056*	.049*	.069	.078	.087	.097	.107	.118
	2	.003*	.003*	.002*	.002*	.002*	.002*	.048*	.040*	.034*	.029*	.025*	.022*	.119	.111*	.093*	.079*	.069*	.060*
	3	.002*	.002*	.002*	.001*	.001*	.001*	.034*	.028*	.024*	.020*	.017*	.015*	.094*	.078*	.065*	.056*	.048*	.042*
	4	.002*	.002*	.001*	.001*	.001*	.001*	.027*	.022*	.019*	.016*	.014*	.012*	.075*	.062*	.052*	.045*	.039*	.034*
	5	.002*	.001*	.001*	.001*	.001*	.001*	.023*	.019*	.016*	.014*	.012*	.010*	.064*	.053*	.045*	.038*	.033*	.029*
1.5	1	.016*	.013*	.011*	.010*	.008*	.007*	.042	.048	.054	.060	.066	.072	.042	.048	.054	.060	.066	.072
	2	.007*	.006*	.005*	.004*	.004*	.003*	.071	.081	.072*	.062*	.053*	.046*	.071	.081	.091	.101	.112	.123
	3	.005*	.004*	.004*	.003*	.003*	.002*	.074*	.062*	.052*	.044*	.038*	.033*	.089	.101	.114	.122*	.105*	.092*
	4	.004*	.004*	.003*	.003*	.002*	.002*	.060*	.050*	.042*	.036*	.031*	.027*	.103	.116	.116*	.099*	.086*	.075*
	5	.004*	.003*	.003*	.002*	.002*	.002*	.052*	.043*	.036*	.031*	.026*	.023*	.113	.119*	.100*	.085*	.073*	.064*
2.0	1	.027*	.023*	.019*	.016*	.014*	.012*	.030	.034	.038	.042	.047	.051	.030	.034	.038	.042	.047	.051
	2	.013*	.011*	.009*	.008*	.006*	.006*	.050	.056	.063	.070	.078	.080*	.050	.056	.063	.070	.078	.085
	3	.009*	.008*	.006*	.005*	.005*	.004*	.062	.070	.079	.077*	.066*	.058*	.062	.070	.079	.087	.096	.106
	4	.008*	.006*	.005*	.004*	.004*	.003*	.070	.080	.074*	.063*	.055*	.047*	.070	.080	.089	.100	.110	.120
	5	.007*	.005*	.005*	.004*	.003*	.003*	.077	.077*	.064*	.055*	.047*	.041*	.077	.087	.098	.109	.120	.114*
3.0	1	.018	.021	.023	.026			.018	.021	.023	.026			.018	.021	.023	.026		
	2	.027*	.023*	.019*	.016*			.030	.034	.038	.042			.030	.034	.038	.042		
	3	.020*	.017*	.014*	.012*	.010*		.037	.042	.047	.052	.058		.037	.042	.047	.052	.058	
	4	.017*	.014*	.012*	.010*	.008*		.042	.047	.053	.059	.065		.042	.047	.053	.059	.065	
	5	.014*	.012*	.010*	.009*	.007*		.046	.052	.058	.065	.071		.046	.052	.058	.065	.071	
4.0	1	.013	.015	.016	.018			.013	.015	.016	.018			.013	.015	.016	.018		
	2	.021	.024	.027	.028*			.021	.024	.027	.030			.021	.024	.027	.030		
	3	.026	.028*	.024*	.020*	.018*		.026	.029	.033	.036	.040		.026	.029	.033	.036	.040	
	4	.029*	.024*	.020*	.017*	.015*		.029	.033	.037	.041	.045		.029	.033	.037	.041	.045	
	5	.025*	.021*	.017*	.015*	.013*		.032	.036	.040	.045	.050		.032	.036	.040	.045	.050	

Not adapted for graded borders * Slope limited by depth requirements

in arid areas, graded border irrigation is not well suited to steeper slopes unless climatic conditions or supplementary irrigation methods can be depended on for establishing good crop stands. Even then, the maximum allowable nonerosive irrigation stream, as defined by equation 4-34, may be too small to permit a practical length of run.

Table 4-11 shows the maximum slope for graded border irrigation, as limited by minimum depth of flow requirements or by a minimum border length of 100 feet. Although table 4-11 indicates the theoretical possibility of using graded border irrigation on very steep slopes, it is much better suited to gentle slopes. On slopes over about 4 percent, erosion is an extreme hazard; it is doubtful whether the graded border method should ever be considered for slopes in excess of 6 percent.

Maximum Length of Run.--The theoretical maximum length of run for graded border irrigation is the length computed by equation 4-23a, using the maximum allowable stream per foot of border strip width (Q_u). The maximum allowable stream is limited by the erosion hazard on steep slopes and by flow capacity of the border strips (allowable flow depth) on the flatter slopes. On some soils of low intake rate on gentle slopes, the theoretical maximum length of run can be several thousand feet. However, as discussed under "Layout Considerations," border lengths in excess of a quarter mile seldom should be designed.

Field Efficiency

Success in designing a graded border layout depends on the ability of the designer to make a reasonable estimate of the field efficiency that can be achieved on a particular site under a given set of management conditions. In most cases, the principal hazard is overestimating efficiency, which leads to designing border strips too long for adequate irrigation at the efficiency that can actually be attained. However, unless one of the design limitations is approached, selection of a design efficiency is not critical. Usually it is possible for the irrigator to adjust stream size enough for the layout designed to operate satisfactorily. In all irrigation methods, efficiency is affected more by the management practices of the irrigator than by any other factor. For a given management level, however, site conditions do have a significant effect on the efficiency achievable in border irrigation. Greater efficiency can be expected on gentle slopes than on steep slopes and on soils that have a moderate to moderately high intake rate than on soils that have either a low or extremely high intake rate.

On gently sloping well-leveled fields, if adequate facilities for the control and distribution of water are installed and good irrigation management practices are followed, a field efficiency of 60 to 75 percent usually is feasible. Table 4-12 shows the efficiencies commonly assumed for designing graded border irrigation.

Table 4-12.--Suggested design efficiency for graded border irrigation by slope and intake family

Irrigation slope s_o	Intake family																															
	0.3				0.5					1.0					1.5					2.0					3.0				4.0			
	Net depth of application (F_n) in inches																															
	1	2	3	4	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	2	3	4
Feet per foot	Percent																															
0.0005	65	65	70	70	65	65	70	70	70	75	75	80	80	80	75	75	80	80	80	75	75	80	80	80	65	70	70	70	65	70	70	70
.0010	60	60	65	65	65	65	70	70	70	70	70	75	75	75	75	75	80	80	80	75	75	80	80	80	65	70	70	70	65	70	70	70
.0020	60	60	55	50	65	65	70	70	70	65	65	70	70	70	70	70	75	75	75	70	70	75	75	75	65	70	70	70	65	70	70	70
.0030	55	55	50		60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	65	70	70	70	65	70	70	70	65	70	70	70
.0040	55	50			60	60	65	60	55	60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	70	70	70	60	65	65	65
.0050	50				60	60	60	55	50	60	60	65	65	65	65	65	70	70	70	65	65	70	70	70	65	70	70	70	60	65	65	65
.0075					55	55	50			60	60	65	65	65	60	60	65	65	65	65	65	70	70	70	65	70	70	70	60	65	65	65
.0100					55	55				60	60	65	65	65	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
.0150					55					55	55	60	60	60	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
.0200					50					55	55	60	55	50	60	60	65	65	65	60	60	65	65	65	60	65	65	65	60	65	65	65
.0250										55	55	55	50		60	60	65	65	65	60	60	65	65	65	60	65	65	65		60	60	60
.0300										55	55	50			55	55	60	60	60	55	55	60	60	60	55	60	60	60		60	60	60
.0400										50	50				55	55	60	60	55		55	60	60	60		60	60	60				
.0500															55	55	60	55	50		55	60	60	60								
.0600															50	50	55	50				55	55	55								

Design Procedure

One or more of the following determinations is needed for designing a layout for graded border irrigation:

1. Stream size needed to irrigate a given length of run.
2. Length of run that can be irrigated with a given stream size.
3. Maximum flow depth expected with a given stream size.
4. Allowable stream size for a given maximum depth of flow.

Before making these determinations, the designer must know or assume a number of design values. The following are items whose design values depend on soil, crop, and topography:

Item	Determinant
Intake family (I_F)	Soil
Irrigation slope (s_o)	Topography (can be changed)
Roughness coefficient (n)	Crop
Net depth of application (F_n)	Soil and crop
Field application efficiency (E)	Slope, soil, and crop
Nonerosive stream size (Q_u)	Slope and crop

The allowable stream size per foot of strip width for low-gradient borders at a given maximum depth of flow can be determined from table 4-9 and for graded borders having slopes greater than 0.4 percent from figure 4-7.

Table 4-7 shows the depth of flow expected in low-gradient borders and figure 4-7 shows the depth expected on slopes over 0.4 percent. Length of run (L) can be found for any given value of Q_u by direct solution of equation 4-23a. T_n, the time required for the infiltration of the desired net irrigation application (F_n), can be determined from the soil intake curve. The recession-lag time (T_L) can be determined from table 4-6 or, for borders steeper than 0.4 percent, from figure 4-7.

A direct solution for the stream size (Q_u) needed for a given length of run (L) is not possible, because the recession-lag time (T_L) on the right-hand side of equation 4-23b is a function of Q_u on the left-hand side. However, the general magnitude of recession-lag time expected for any given slope and intake opportunity time can be estimated from table 4-6 or figure 4-7, and Q_u determined by trial-and-error solution of equation 4-23b. (See sample calculation 4-2.) Usually there is no practical significance in attempting to determine the recession-lag time closer than the nearest whole minute.

Design Charts

To simplify design procedure, a series of design charts have been prepared. Each chart is for a single intake family (I_F), a single roughness coefficient (n), and a single net depth of application (F_n). These charts for n values of 0.04, 0.15, and 0.25 are in appendices D, E, and F.

Sample Calculation 4-2.--Trial-and-Error Solution of Equation 4-23b

Given:

Intake family (I_F)	0.5
Net depth of application (F_n)	4 inches
Irrigation slope (s_o)	0.001 feet per foot
Roughness coefficient (n)	0.15
Estimated field application efficiency (E)	65 percent
Length of run (L)	650 feet

Find:

Required unit-width stream size (Q_u)

Required time of application (T_a)

Solution:

T_n = 328 minutes (from intake curve)

T_L ≈ 8 to 20 minutes (from table 4-6)

First trial:

Assume T_L = 14 minutes

$$Q_u = \frac{LF_n}{7.2(T_n - T_L)E} = \frac{(650)(4.0)}{(7.2)\ (328 - 14)(65)} = 0.018 \text{ cubic feet per second}$$

For Q_u = 0.018 T_L = 12 minutes (from table 4-6)

Second trial:

Assume T_L = 12 minutes

$$Q_u = \frac{(650)(4.0)}{(7.2)(328 - 12)(65)} = 0.018 \text{ cubic feet per second} \quad \text{OK}$$

T_a = 328 - 12 = 316 minutes

Check flow depth and stream size

Maximum depth of flow (d_1) = 0.15 feet (from table 4-7) OK

Minimum allowable Q_u = (0.00001349) (650) = 0.0088 (from table 4-10) OK

Note: Unless the recession-lag time (T_L) is expected to be more than 25 percent of the required opportunity time (T_n), the first estimate of T_L provides for a sufficiently accurate estimate of the needed unit-width stream (Q_u).

The charts show the relationship between stream size and length of run for any given or assumed efficiency value by plotting the nondimensional ratio, length/efficiency as the abscissa and the stream size as the ordinate. Thus, if the designer wishes to find the length of run that can be irrigated with a given size of stream per foot of border strip width and a given efficiency, he determines the length-efficiency ratio for the given stream size and irrigation slope and multiplies this value by the given efficiency value.

The charts also show relationships between stream size and depth of flow and the required time of application. Depth, length-efficiency ratio, and time curves are shown for the full range of slopes for which graded borders are suitable. The maximum slope shown is the lesser of: (1) the steepest slope on which the minimum flow depth requirements can be met when irrigated at 50 percent efficiency; (2) the steepest slope that can be irrigated safely with a minimum length of run of 100 feet; or (3) 6 percent. The maximum nonerosive stream sizes are shown for sod-forming crops by the termination of the depth curves and by the tick mark (-) on the depth curves for nonsodforming crops. On all the charts the length-efficiency ratio is limited to a value of 30, which is equivalent to a length of 1,500 feet at 50 percent efficiency and proportionately longer lengths at higher efficiencies. Figure 4-8 is a sample chart of an 0.15 n value, a 1.0 intake family, and a 4-inch net depth of application.

These design charts are arranged so that for any selected efficiency almost any other known or assumed value can be used as a starting point; however, the charts should not be used to find efficiency values. For example, if a field having an irrigation grade of 0.4 percent (s_o = 0.004 feet per foot) has border strips 1,300 feet long, the needed stream size per foot of border strip width, the maximum flow depth, and the required time of application can be determined from the chart for any given or assumed efficiency. If it is assumed that the field can be irrigated at 65 percent efficiency, the length-efficiency ratio (1,300/65) is 20. For this value and a slope of 0.004 feet per foot, the required unit width stream is 0.072 cubic feet per second, the maximum depth of flow is 0.265 foot, and the time of application is 156 minutes.

In the above example, if the flow depth could not exceed 0.20 foot, the stream size would have to be reduced to 0.044 cubic feet per second, which would provide for a length-efficiency ratio of 12.1 or a border length of 790 feet. To find the maximum length of run for a slope of 2 percent and 55 percent efficiency, find the maximum nonerosive stream size for a nonsodforming crop opposite the dot on the proper depth curve. Follow this stream size (0.036 cfs) to the intersection with the length-efficiency ratio curve for a slope of 2 percent. The length-efficiency ratio is 10.1, and the maximum length of run is 555 feet (10.1 x 55).

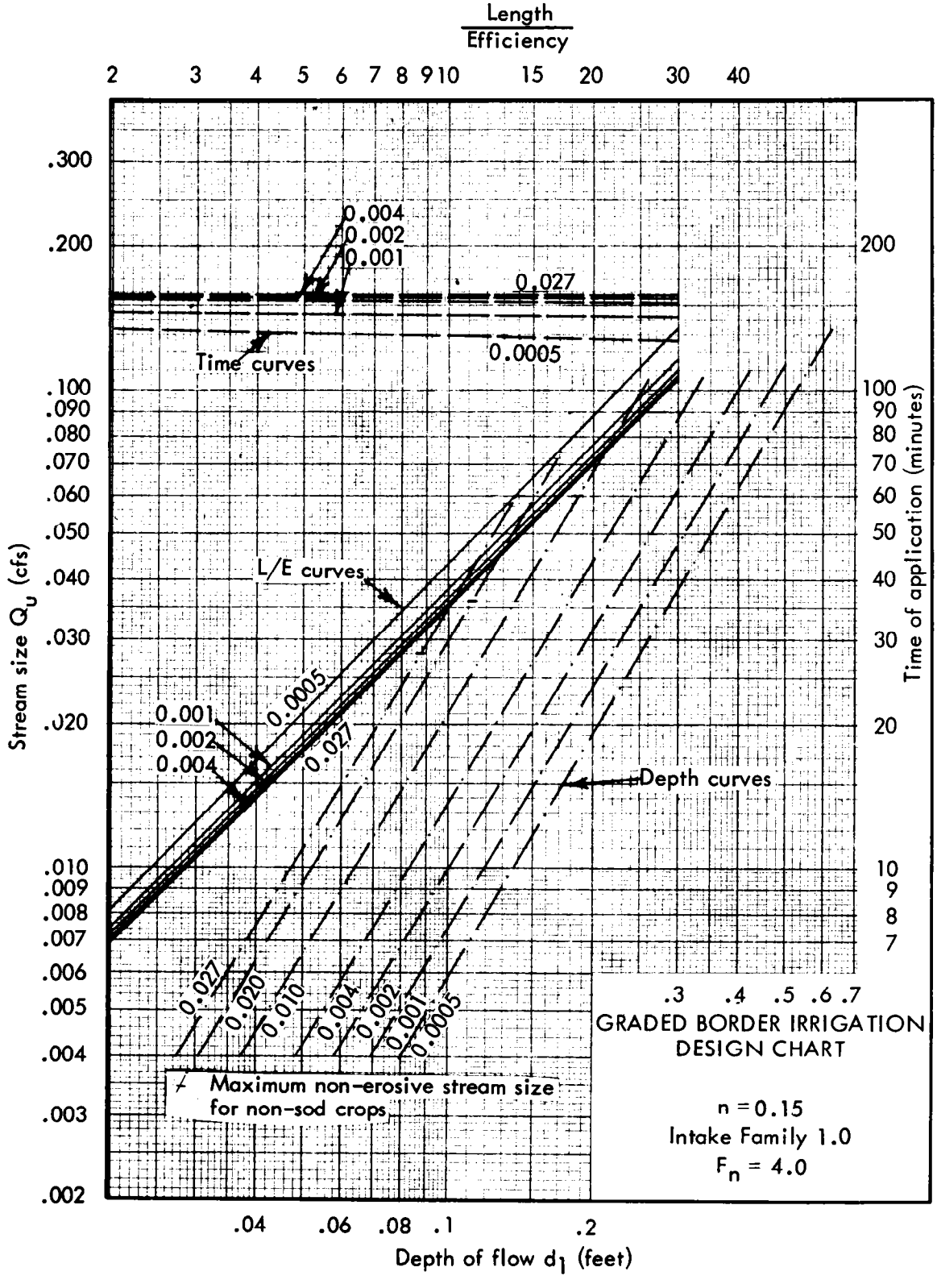


Figure 4-8.--Sample design chart for graded border irrigation

Use of End Blocks

Using end blocks to impound water that otherwise would be runoff or tailwater can result in a considerably higher application efficiency provided the impoundment affects a significant area. As a rule, if the net depth of application equals or exceeds 5 percent of the total fall in the length of the border strip, the use of end blocks should be considered in planning and design (see table 4-13).

Table 4-13.--Maximum border lengths for using end blocks by slope and net depth of application

Irrigation slope s_o	Net depth of application (F_n) in inches				
	1	2	3	4	5
Feet per foot			Feet		
0.0005	3,333				
.0010	1,667				
.0020	833	1,667			
.0030	556	1,112	1,667		
.0040	417	833	1,250	1,667	
.0050	333	666	1,000	1,332	1,667
.0075	222	444	667	889	1,112
.0100	167	333	500	667	834
.0150	111	222	333	444	556
.0200		167	250	333	416
.0250		134	202	269	336
.0300		111	167	222	278
.0400			125	167	208
.0500			100	133	167
.0600				111	139

End blocks should not impound water to depths more than 1-1/2 times the depth of the net application, unless the area can be drained immediately after the required intake opportunity time has been met. Drainage is needed to avoid (1) excessive deep percolation, (2) crop damage from standing water, and (3) mosquito breeding. If surface drainage of rainfall is a problem, provision must be made for releasing this excess water.

Border ridges must be greater in height than the depth of water in the ponded area. All or part of that portion of the irrigation application that otherwise would be runoff can be held on the field, thus increasing the length of run that can be served by a given irrigation stream. Sites with soils of low intake rate, steep irrigation grade, or low roughness coefficient usually have more water available for impoundment than sites with soils of high intake rate, gentle irrigation grade, or high roughness coefficient.

The distance border strips can be lengthened by using end blocks is limited to the lesser of:

1. The length that can be covered by an impoundment whose maximum depth is equal to the desired net application depth

$$L_e = F_n/12\ s_o \qquad \text{(Eq. 4-39)}$$

2. The length that can be adequately irrigated with the volume of water that would run off the open-end border strip

$$L_e = (1.00 - E/100)\ r_i\ r_n\ L \qquad \text{(Eq. 4-40)}$$

In equations 4-39 and 4-40, L is the normal design length of run for open-end borders, L_e is the allowable length extension with end blocks, r_i and r_n are factors that express the effect of intake and roughness on runoff. Empirical values for these factors are given in table 4-14.

Table 4-14.--Intake and roughness factors for estimating potential runoff

Intake family	Factor (r_i)	Roughness coefficient (n)	Factor (r_n)
0.1	1.00	0.04	0.90
0.3	.90	.10	.80
0.5	.80	.15	.75
1.0	.70	.20	.70
1.5	.65	.25	.65
2.0	.60		
3.0	.50		
4.0	.40		

On sites where the irrigation grade is steep enough to make condition (1) limiting, the allowable extension can be increased to that computed under condition (2) by grading the field so the lower end of the run is level or nearly level. (See sample calculation 4-3 for the effect of end blocks on application efficiency and allowable length of run.) On fields where the length of run is fixed, using end blocks does not change the length but does permit using a reduced unit-width stream (Q_u'). The required stream size is that needed for a length of run (L') where this length plus the allowable extension (L_e') is equal to the fixed length L (see figure 4-9).

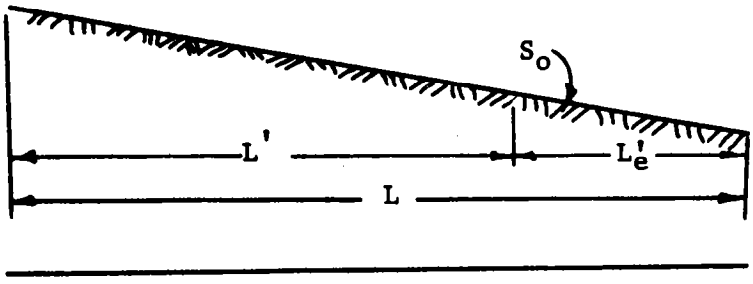


Figure 4-9.--Diagram of end block length extension

Length extensions are proportional to original lengths as shown by equation 4-40. Therefore:

$$L/L_e = L'/L'_e \qquad \text{(Eq. 4-41)}$$

or

$$L'_e = \frac{L' L_e}{L} \qquad \text{(Eq. 4-42)}$$

and

$$L' + \frac{L' \; L_e}{L} = L \qquad \text{(Eq. 4-43)}$$

Then

$$L' = \frac{L}{1 + \frac{L_e}{L}} \qquad \text{(Eq. 4-44)}$$

If L' is known, the required stream size (Q'_u) can be computed by a trial-and-error procedure (see sample calculation 4-2). But since the reduction in stream size is likely to be enough to make a significant change in recession-lag time, the stream size is proportional to length and can be computed directly.

$$Q'_u = \frac{Q_u}{1 + \frac{L_e}{L}} \qquad \text{(Eq. 4-45)}$$

If equations 4-45 and 4-40 are combined, the required stream size can be related to estimated runoff as follows:

$$Q'_u = \frac{Q_u}{1 + (1.00 - E/100)\; r_i \; r_n} \qquad \text{(Eq. 4-46)}$$

Sample calculation 4-3.--Effect of end blocks on field application efficiency and length of run

Given:

Intake family (I_F)	1.0
Net depth of application (F_n)	3 inches
Irrigation slope (s_o)	0.001 feet per foot
Roughness coefficient (n)	0.15
Estimated field application efficiency (E)	75 percent
Allowable depth of flow at head of run (d_1)	0.3 feet

Find:

Allowable stream size (Q_u)
Required time of application (T_a)
Maximum length of run for open-end borders (L)
Allowable length extension with end blocks (L_e)
Efficiency with end blocks (E)

Solution:

T_n = 106 minutes (from intake curve)

Q_u = 0.049 cubic feet per second (from table 4-9)

T_L = 11 minutes (from table 4-6)

$T_a = (T_n - T_L) = 106 - 11 = \underline{95}$ minutes

$L = (7.2)(0.049)(106 - 11)(75)/3.0 = \underline{838}$ feet (Eq. 4-23a)

$L_e = 3.0/(12)(0.001) = 250$ feet (Eq. 4-39)

$L_e = (1.00 - 0.75)(0.70)(0.75)(838) = \underline{110}$ feet (Eq. 4-40)

$F_g = (720)(0.049)(106 - 11)/(838 + 110) = 3.54$ inches

$E = 3.0/3.54 = 0.85 = \underline{85}$ percent

As an example of this procedure, the stream size computed for the open-end borders 838-feet long, described in sample calculation 4-3, is 0.049 cubic feet per second. Using equation 4-46, the stream size needed for closed borders 838 feet long is:

$$Q_u' = \frac{0.049}{1 + (1.00 - 75/100)(0.70)(0.75)} = 0.0433 \text{ cubic feet per second}$$

The gross depth of application and resulting application efficiency are computed as follows:

$$F_g = 720\ Q_u(T_n - T_L)/L = (720)(0.0433)(106-11)/836 = 3.53 \text{ inches}$$

$$E = F_n/F_g = 3.0/3.53 = 0.85 = 85 \text{ percent}$$

Guide Border

In guide border irrigation, water is turned into the upper end of a sloping border strip and is allowed to run until a sufficient amount has infiltrated the soil. The stream size is not determined by the intake characteristics of the soil; it is determined by the hydraulic characteristics of the site. The stream must be large enough to provide adequate spreading over the strip, but it must not be so large as to cause erosion.

Adaptability

Guide border irrigation is used primarily to irrigate grasses, legumes, and grass-legume mixtures. It is also used to irrigate small grains customarily grown in rotation with the grasses and legumes. It is best suited to soils that have a moderate to very low intake rate. It is seldom used on soils in the 1.0 or higher intake families.

Guide borders are used on slopes as low as 0.1 percent where application depths of 1.5 inches or more are required on soils of very low intake rate (0.1 and 0.3 intake families). They are used on slopes as low as 0.3 or 0.4 percent for orchards with no cover crop on soils in the 1.0 intake family. For crops like alfalfa grown on soils in this intake family, guide borders may be suitable only on slopes steeper than 3.5 or 4.0 percent. Graded borders are used on the more gentle slopes.

Advantages

Since the stream size used is only large enough to insure complete coverage of the border strip, border ridges usually need to be no more than 2 or 3 inches high. There is little danger of their being overtopped and washed out. Costs of preparing land are low because the border strips are narrow. They are no wider than the length of the grading equipment blade, and the earth that spills around the ends of the blade forms the ridges. Each border strip can be leveled independently of the others. A considerable variation in downfield slope is acceptable as long as there are no grade reversals and all cross slope is eliminated.

Limitations

The major difficulty in using guide borders is irrigating new seedings adequately without causing erosion. On the steeper slopes it may be desirable to irrigate with sprinklers until a good crop stand has been established. On slopes up to 2 or 3 percent, shallow corrugations can be used to help keep the water spread over the border strip. Another limitation is the amount of surface runoff that must be handled. Since an irrigating stream large enough to insure spread over the border strip is larger than the stream needed to satisfy intake, a considerable part of the applied water runs off the lower end of the strip. Unless the runoff is collected for reuse, application efficiency is very low. This kind of irrigation also requires much labor, and the irrigator needs considerable skill to do a good job without causing excessive erosion.

Design Assumptions

Guide border irrigation is used where the irrigating stream needed to satisfy intake requirements and provide a balance between advance and recession for graded border irrigation is too small to spread over the border strip. This condition can be expected on steep slopes and on soils having a low intake rate. These strips can be irrigated satisfactorily by using the smallest stream that spreads adequately across the border strip and applying this stream for the time required for the soil at the upper end of the guide border strip to absorb the desired net depth of application.

Since the stream required for adequate spread is larger than needed to satisfy intake, much surface runoff can be anticipated and must be collected and reused or otherwise disposed of safely. The amount of runoff can be minimized by using the smallest stream that can spread out and completely cover the border strip.

Design Equations

Equation 4-36 describes the minimum stream needed per foot of border strip width to provide an adequate spread of water over strips that are reasonably well graded and smoothed.

$$Q_u = 0.000064\ L\ s_o^{0.5}/n \qquad \text{(Eq. 4-36)}$$

Table 4-10 shows minimum values of Q_u/L for various slopes and n values. Figures 4-10 and 4-11 show the relationship between stream size (Q_u) and length of run (L), as described by equation 4-36, for n values of 0.15 and 0.25 respectively.

Design Limitations

Minimum Slopes.--Guide border irrigation should be restricted to slopes that are too steep to be irrigated by graded borders at an acceptable efficiency level. Guide borders are designed only for slopes steeper than those shown in table 4-11 as limited by depth requirements. They cannot be used on slopes steeper than those shown as limited by the length of run requirement unless a border length of less than 100 feet is acceptable.

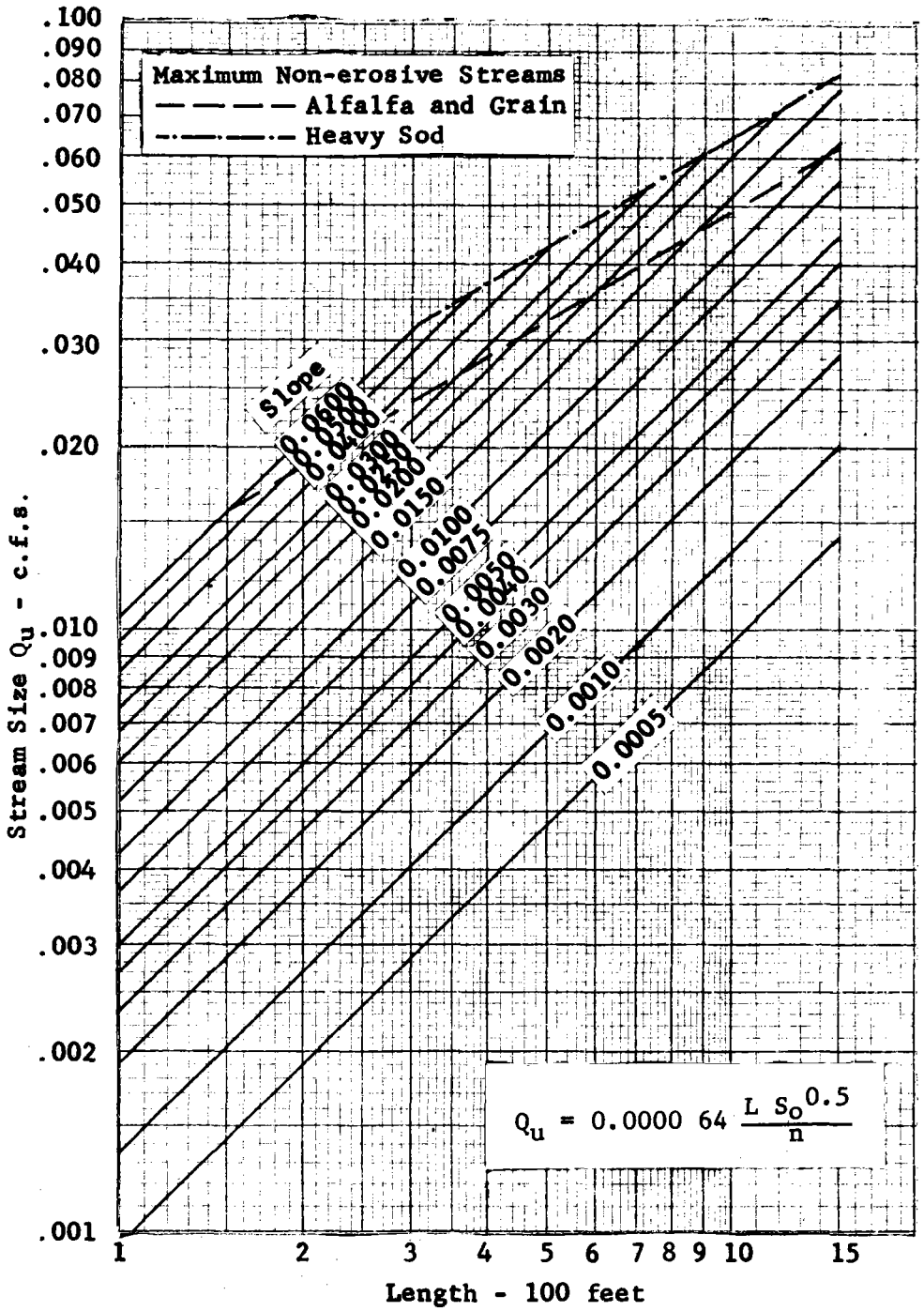


Figure 4-10.--Stream size and length of run relationship for guide border design when n = 0.15

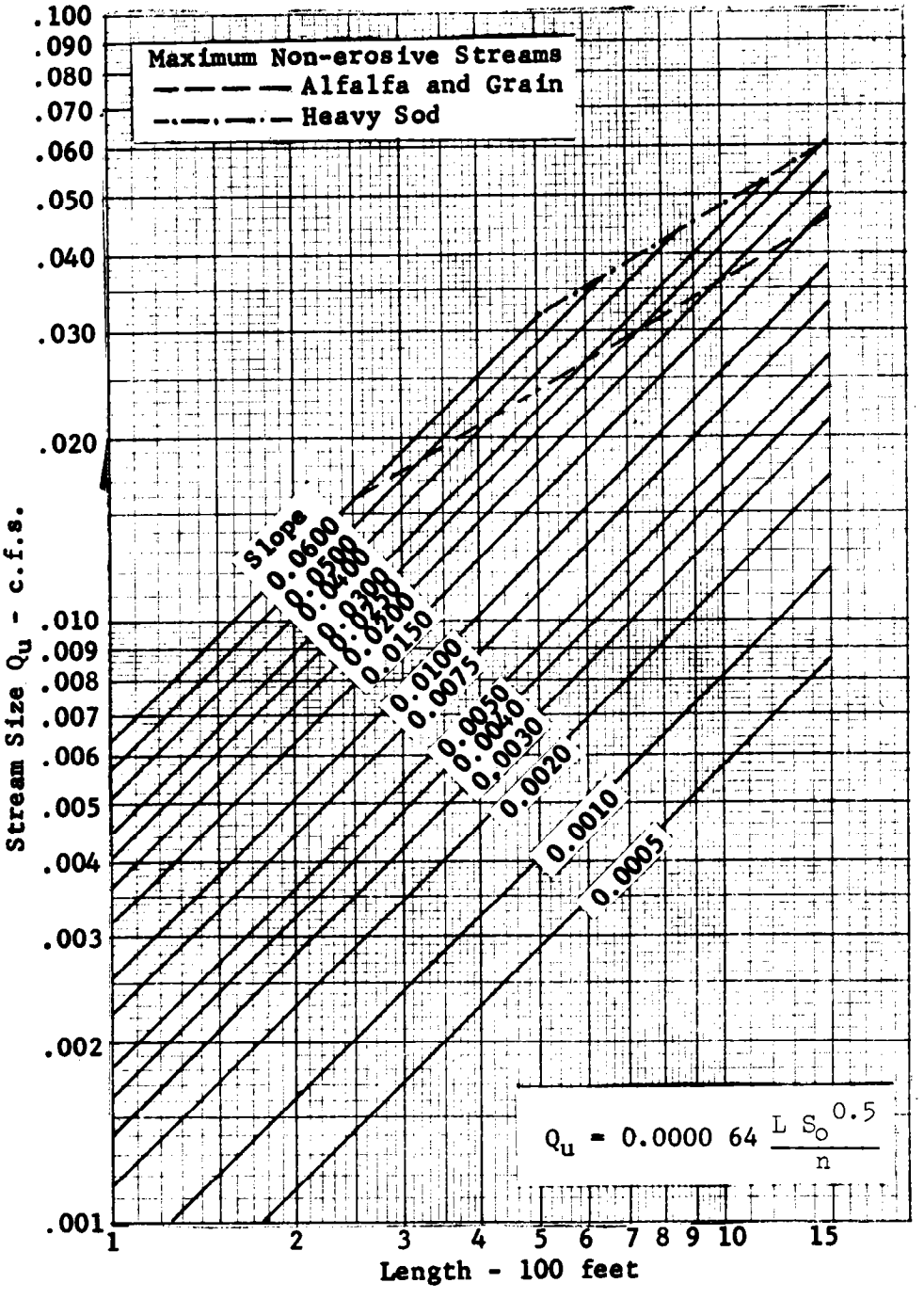


Figure 4-11.--Stream size and length of run relationship for guide border design when n = 0.25

Maximum Depth of Application.--The gross depth of application (F_g) that must be run onto a guide border strip is equal to the minimum required flow rate per foot of strip width multiplied by the required intake opportunity time and divided by the length of the border strip.

$$F_g = 720\ T_n\ Q_u/L \qquad \text{(Eq. 4-47)}$$

The gross depth of application must not be so great that the required volume exceeds the available supply. Also, the excess depth applied ($F_g - F_n$), which will be largely surface runoff, must not be more than can feasibly be collected and stored for reuse, conveyed to a field for immediate reuse, or returned safely to a natural stream or an irrigation conveyance system for eventual downstream reuse.

Tables 4-15, 4-16, 4-17, and 4-18 show the gross depth of application required for guide borders on soils in intake families 0.1, 0.3, 0.5 and 1.0. Developed from equation 4-47, these tables show the gross depth requirement for n values of 0.15 and 0.25. Soils in intake families 1.5 and higher generally are not irrigated in this way unless the roughness coefficient (n) is less than 0.15. This condition is found in some orchards and vineyards if cover crops are sparse or nonexistent. With little or no vegetative protection, erosion is an extreme hazard on all but the most gentle slopes.

Construction Requirements

Land Leveling.--Guide borders have very shallow depths of flow. Therefore, the surface of the border strip must be made as smooth as is practicable with the usual land grading equipment. It is especially important that all side slope be removed. To insure a perfectly smooth transverse surface, guide border strips usually are made only as wide as the blade used in leveling. A leveling device is often attached to the blade to keep it exactly horizontal as the equipment travels up and down the border strip. Every precaution must be taken to reduce the possibility of leaving longitudinal low areas on which the flows can concentrate. It is easier to prepare border strips on well-leveled fields on which all cross slope has been removed. On relatively smooth natural slopes, however, guide border strips often are formed without prior leveling of the field. Each strip is graded independently. Attention is given to removing side slope. Longitudinal grades are smoothed, but usually no effort is made to make them uniform.

Border Ridges.--Since the flow depth in guide borders is shallow, border ridges usually need to be only a few inches high. Flow depth seldom exceeds 2 inches, and border ridges having a settled height of about 3 inches are adequate. Higher ridges may be needed for extra-long guide borders on very gentle slopes.

Table 4-15.--Required time of irrigation and gross depth of application for guide borders on 0.1 intake family soils

Irrigation slope	Minimum Q_u/L	F_n = 1.0 T_a = 169	F_n = 1.5 T_a = 374	F_n = 2.0 T_a = 628	F_n = 2.5 T_a = 923	F_n = 3.0 T_a = 1255
Feet per foot		Gross depth of application (Inches)				
				n = 0.15		
0.0005	0.00000954	1.16	2.57	4.31	6.34	8.62
.0010	.00001349	1.64	3.63	6.10	8.97	12.19
.0020	.00001908	2.32	5.14	8.63	12.68	
.0030	.00002337	2.84	6.29			
.0040	.00002699	3.28	7.27			
.0050	.00003017	3.67				
.0075	.00003695	4.50				
.0100	.00004267					
.0150	.00005227					
.0200	.00006033					
.0250	.00006745					
.0300	.00007390					
.0400	.00008533					
.0500	.00009540					
.0600	.00010449					
				n = 0.25		
.0005	.00000572	*	*	*	*	*
.0010	.00000810	*	*	*	5.38	7.32
.0020	.00001145	*	*	5.18	7.61	10.35
.0030	.00001402	*	3.78	6.34	9.32	12.67
.0040	.00001619	*	4.36	7.32	10.76	14.63
.0050	.00001810	2.20	4.87	8.18	12.03	
.0075	.00002217	2.70	5.97	10.02		
.0100	.00002560	3.12	6.89			
.0150	.00003136	3.82				
.0200	.00003620	4.40				
.0250	.00004047	4.92				
.0300	.00004434					
.0400	.00005120					
.0500	.00005724					
.0600	.00006270					

*Not adapted for guide borders. Values are omitted where $F_g > 5F_n$.

Table 4-16.--Required time of irrigation and gross depth of application for guide borders on 0.3 intake family soils

Irrigation slope	Minimum Q_u/L	F_n = 1.0 T_a = 62	F_n = 1.5 T_a = 129	F_n = 2.0 T_a = 208	F_n = 3.0 T_a = 392	F_n = 4.0 T_a = 604
Feet per foot		Gross depth of application (Inches)				
		n = 0.15				
0.0005	0.00000954	*	*	*	*	*
.0010	.00001349	*	*	*	*	*
.0020	.00001908	*	*	*	*	*
.0030	.00002337	*	*	*	*	10.16
.0040	.00002699	*	*	*	7.62	11.74
.0050	.00003017	*	*	4.52	8.52	13.12
.0075	.00003695	*	3.43	5.53	10.43	16.07
.0100	.00004267	*	3.96	6.39	12.04	18.56
.0150	.00005227	2.33	4.85	7.83	14.75	
.0200	.00006033	2.69	5.60	9.04		
.0250	.00006745	3.01	6.26	10.10		
.0300	.00007390	3.30	6.86			
.0400	.00008533	3.81				
.0500	.00009540	4.26				
.0600	.00010449	4.66				
		n = 0.25				
.0005	.00000572	*	*	*	*	*
.0010	.00000810	*	*	*	*	*
.0020	.00001145	*	*	*	*	*
.0030	.00001402	*	*	*	*	*
.0040	.00001619	*	*	*	*	*
.0050	.00001810	*	*	*	*	*
.0075	.00002217	*	*	*	6.26	9.64
.0100	.00002560	*	*	*	7.23	11.13
.0150	.00003136	*	*	4.70	8.85	13.64
.0200	.00003620	*	3.36	5.42	10.22	15.74
.0250	.00004047	*	3.76	6.06	11.42	17.60
.0300	.00004434	*	4.12	6.64	12.51	19.28
.0400	.00005120	2.29	4.76	7.67	14.45	
.0500	.00005724	2.56	5.32	8.57		
.0600	.00006270	2.80	5.82	9.39		

*Not adapted for guide borders. Values are omitted where $F_g > F_n$.

Table 4-17.--Required time of irrigation and gross depth of application for guide borders on 0.5 intake family soils

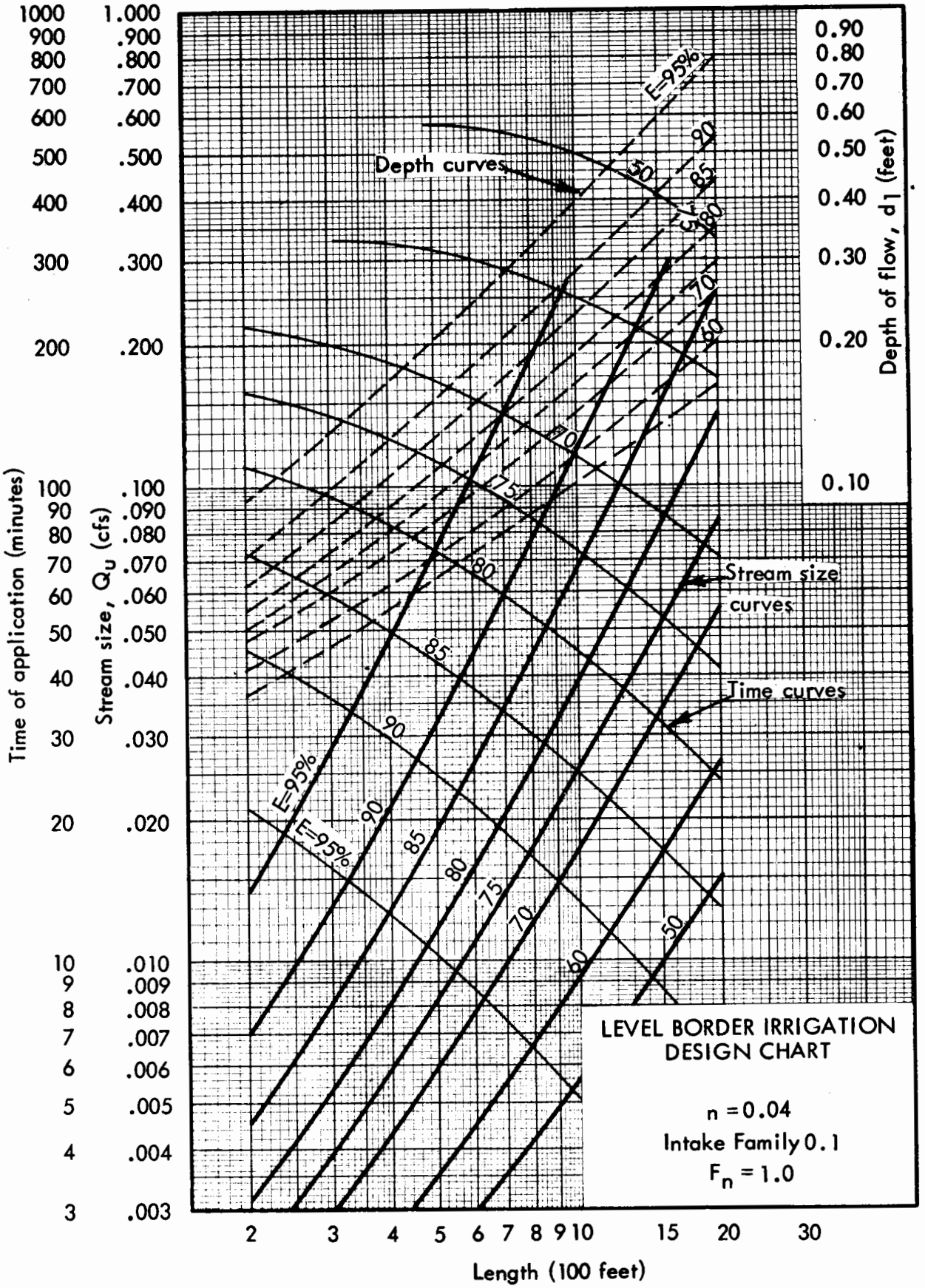
Irrigation slope	Minimum Q_u/L	F_n = 1.0 T_a = 38	F_n = 2.0 T_a = 119	F_n = 3.0 T_a = 217	F_n = 4.0 T_a = 328	F_n = 5.0 T_a = 450
Feet per foot		Gross depth of application (Inches)				
		n = 0.15				
0.0005	0.00000954	*	*	*	*	*
.0010	.00001349	*	*	*	*	*
.0020	.00001908	*	*	*	*	*
.0030	.00002337	*	*	*	*	*
.0040	.00002699	*	*	*	*	*
.0050	.00003017	*	*	*	*	*
.0075	.00003695	*	*	*	8.73	11.97
.0100	.00004267	*	*	6.67	10.08	13.82
.0150	.00005227	*	4.48	8.17	12.34	16.94
.0200	.00006033	*	5.17	9.43	14.25	19.55
.0250	.00006745	*	5.78	10.53	15.93	21.85
.0300	.00007390	*	6.33	11.55	17.45	23.94
.0400	.00008533	2.33	7.31	13.33	20.15	
.0500	.00009540	2.61	8.17	14.91		
.0600	.00010449	2.86	8.95			
		n = 0.25				
.0005	.00000572	*	*	*	*	*
.0010	.00000810	*	*	*	*	*
.0020	.00001145	*	*	*	*	*
.0030	.00001402	*	*	*	*	*
.0040	.00001619	*	*	*	*	*
.0050	.00001810	*	*	*	*	*
.0075	.00002217	*	*	*	*	*
.0100	.00002560	*	*	*	*	*
.0150	.00003136	*	*	*	*	*
.0200	.00003620	*	*	*	8.55	11.73
.0250	.00004047	*	*	6.32	9.56	13.11
.0300	.00004434	*	*	6.93	10.47	14.37
.0400	.00005120	*	4.39	8.00	12.09	16.59
.0500	.00005724	*	4.90	8.94	13.52	18.55
.0600	.00006270	*	5.37	9.80	14.81	20.31

*Not adapted for guide borders. Values are omitted where $F_g > 5F_n$.

Table 4-18.--Required time of irrigation and gross depth of application for guide borders on 1.0 intake family soils

Irrigation slope	Minimum Q_u/L	$F_n = 1.0$ $T_a = 20$	$F_n = 2.0$ $T_a = 59$	$F_n = 3.0$ $T_a = 106$	$F_n = 4.0$ $T_a = 158$	$F_n = 5.0$ $T_a = 214$
Feet per foot		Gross depth of application (Inches)				
		n = 0.15				
0.0005	0.00000954	*	*	*	*	*
.0010	.00001349	*	*	*	*	*
.0020	.00001908	*	*	*	*	*
.0030	.00002337	*	*	*	*	*
.0040	.00002699	*	*	*	*	*
.0050	.00003017	*	*	*	*	*
.0075	.00003695	*	*	*	*	*
.0100	.00004267	*	*	*	*	*
.0150	.00005227	*	*	*	*	*
.0200	.00006033	*	*	*	*	*
.0250	.00006745	*	*	*	*	10.39
.0300	.00007390	*	*	*	8.41	11.39
.0400	.00008533	*	*	6.51	9.71	13.15
.0500	.00009540	*	4.05	7.28	10.85	14.70
.0600	.00010449	*	4.44	7.97	11.89	16.10
		n = 0.25				
.0005	.00000572	*	*	*	*	*
.0010	.00000810	*	*	*	*	*
.0020	.00001145	*	*	*	*	*
.0030	.00001402	*	*	*	*	*
.0040	.00001619	*	*	*	*	*
.0050	.00001810	*	*	*	*	*
.0075	.00002217	*	*	*	*	*
.0100	.00002560	*	*	*	*	*
.0150	.00003136	*	*	*	*	*
.0200	.00003620	*	*	*	*	*
.0250	.00004047	*	*	*	*	*
.0300	.00004434	*	*	*	*	*
.0400	.00005120	*	*	*	*	*
.0500	.00005724	*	*	*	*	*
.0600	.00006270	*	*	*	*	*

*Not adapted for guide borders.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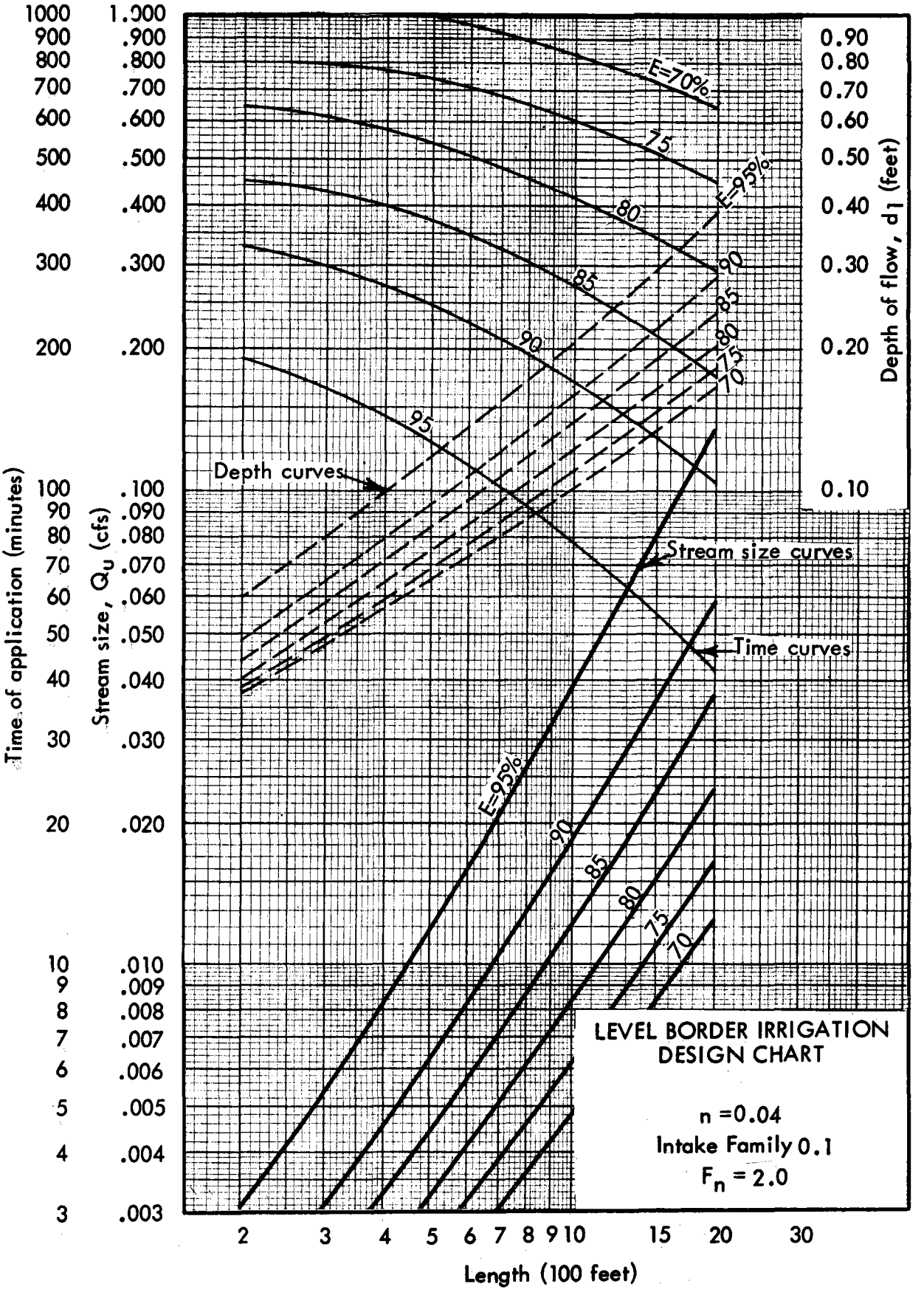
n = 0.04
Intake Family 0.1
F_n = 1.0
Depth curves
Stream size curves
Time curves
E=95%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)


Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=70%
75
80
85
90
95
E=95%
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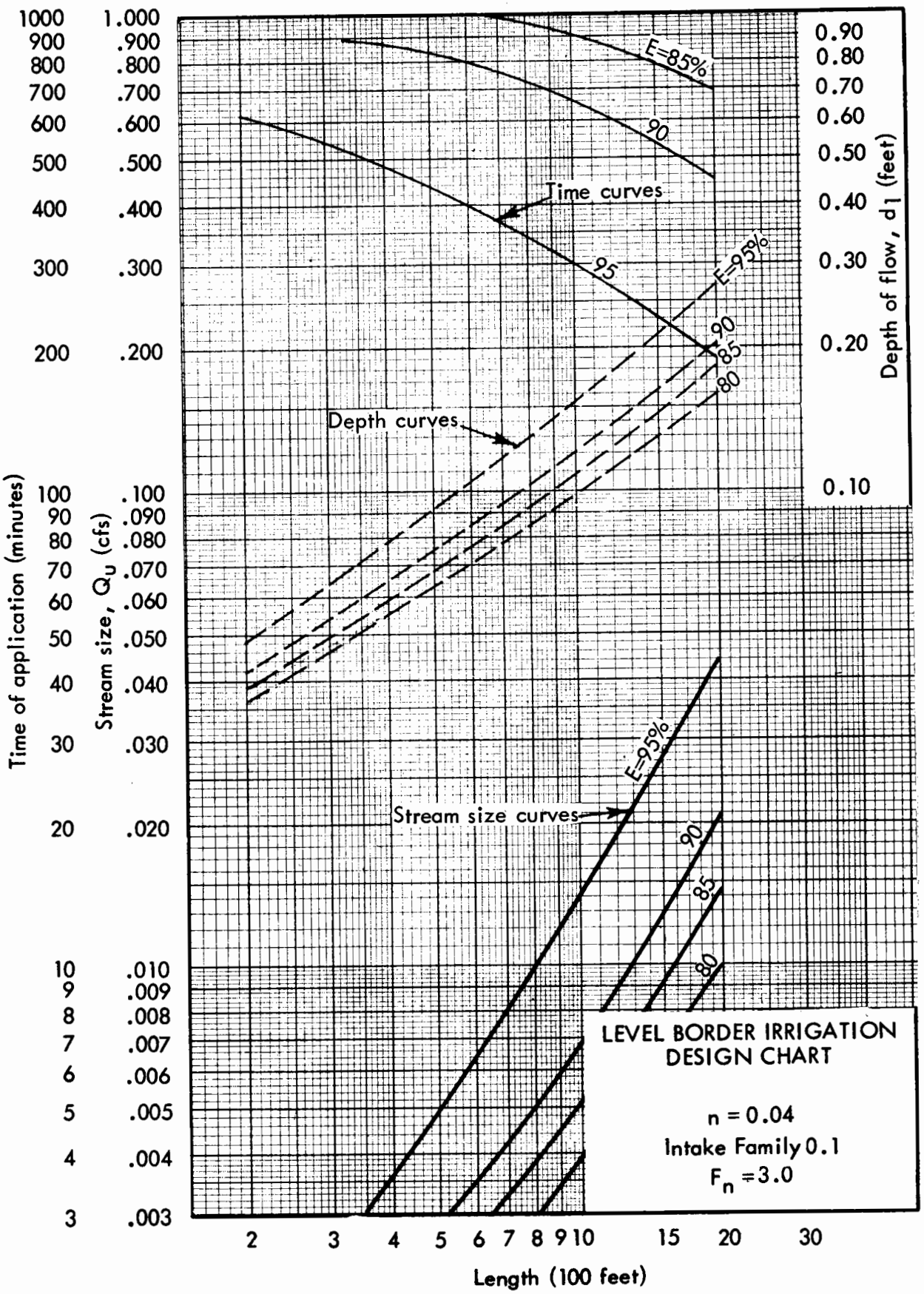
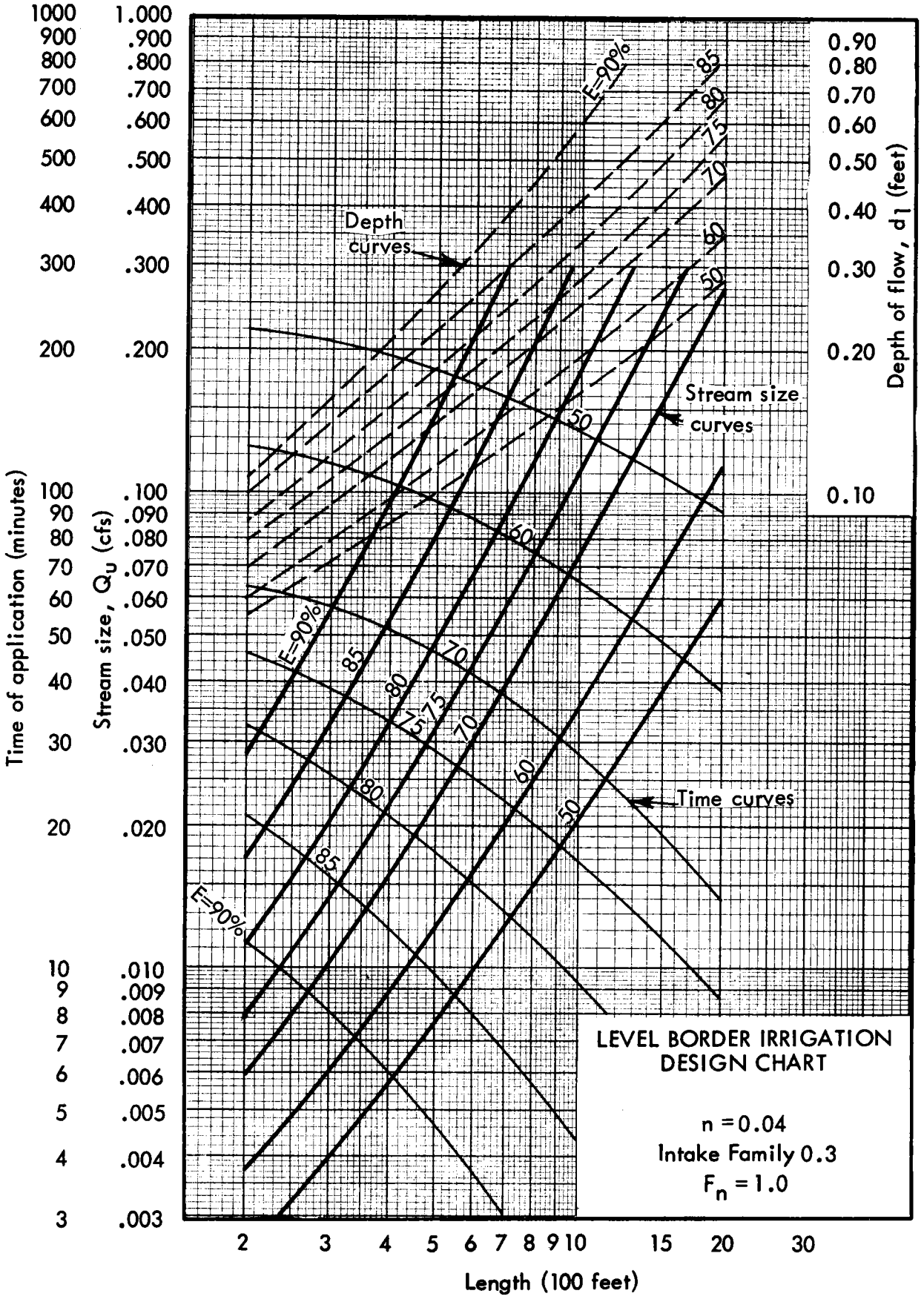
Intake Family 0.1
F_n = 2.0


Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=85%
90
95
E=95%
90
85
80
E=95%
90
85
80
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.1
F_n = 3.0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Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
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Stream size curves
Time curves
E=90%
85
80
75
70
60
50
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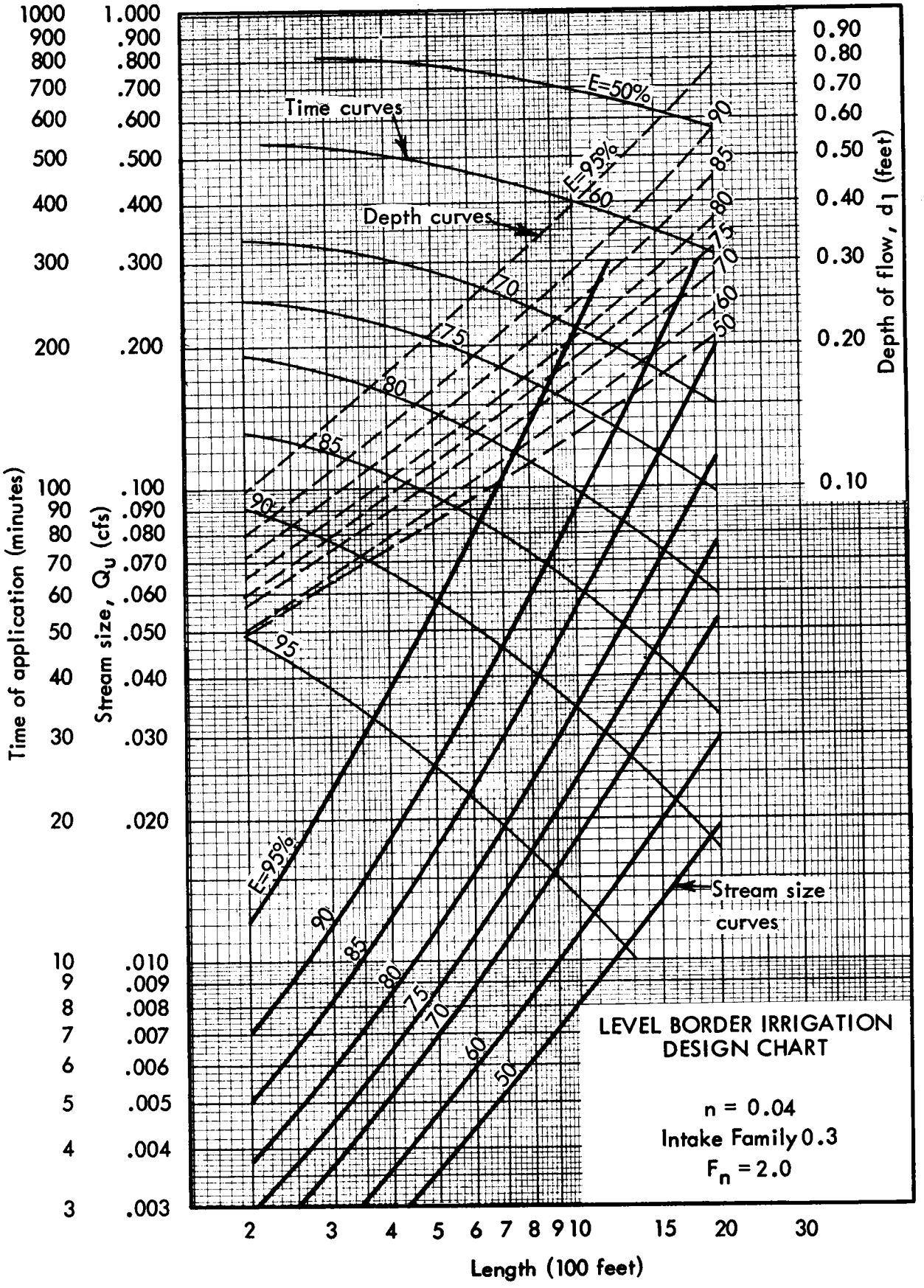
Intake Family 0.3
F_n = 1.0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Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
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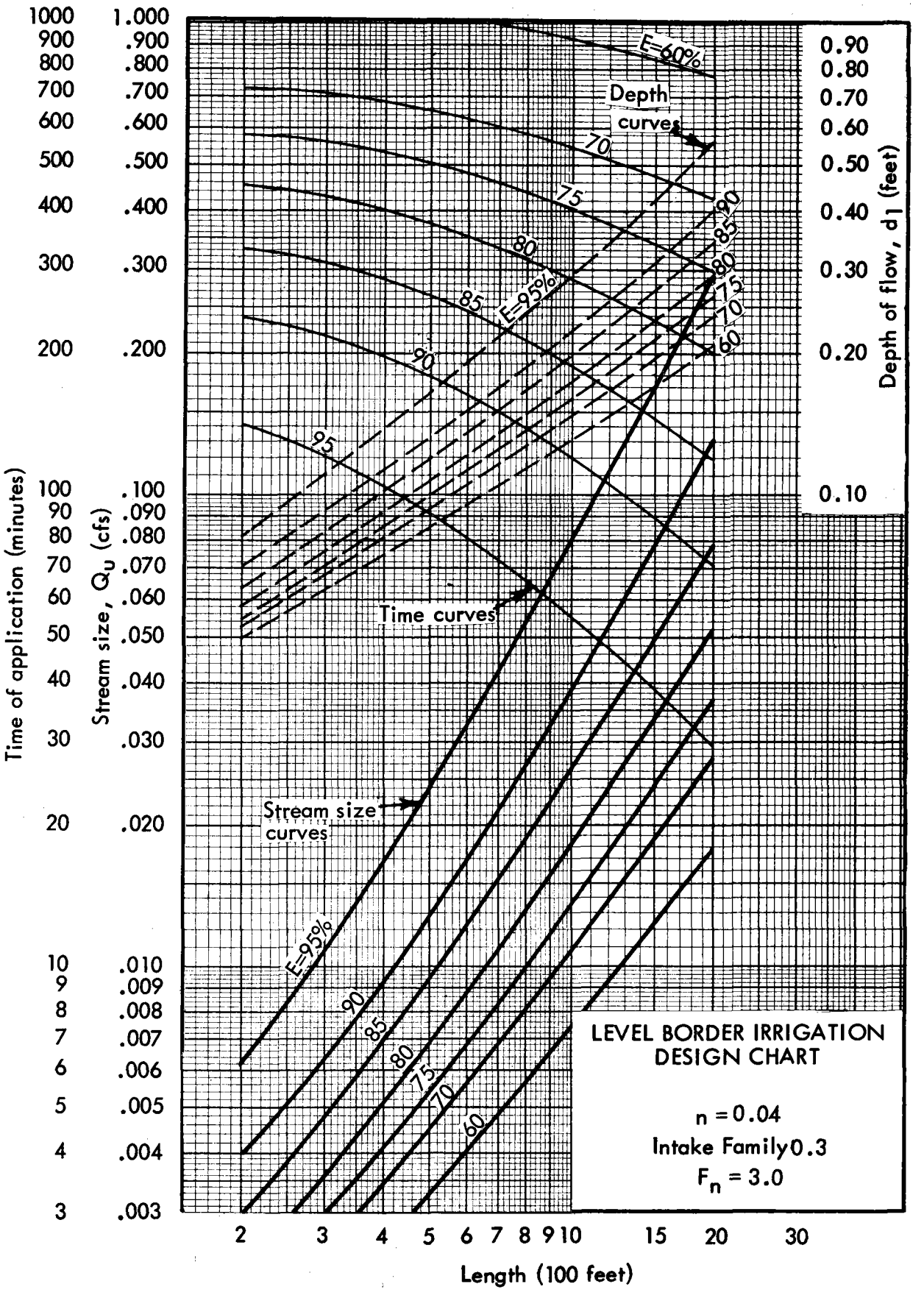
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.3
F_n = 2.0


Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
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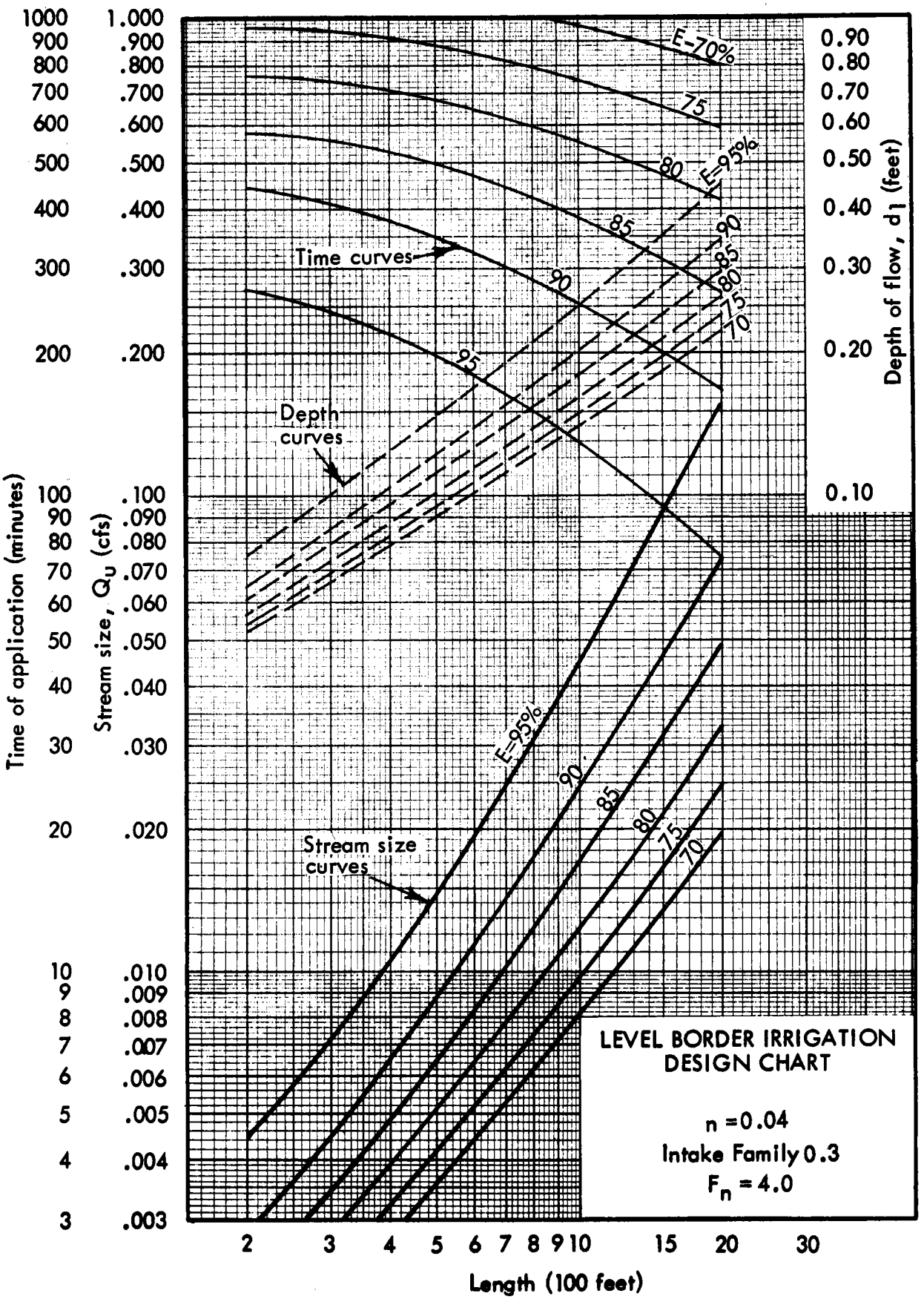
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.3
F_n = 3.0


Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=70%
75
80
85
90
95
E=95%
90
85
80
75
70
LEVEL BORDER IRRIGATION DESIGN CHART
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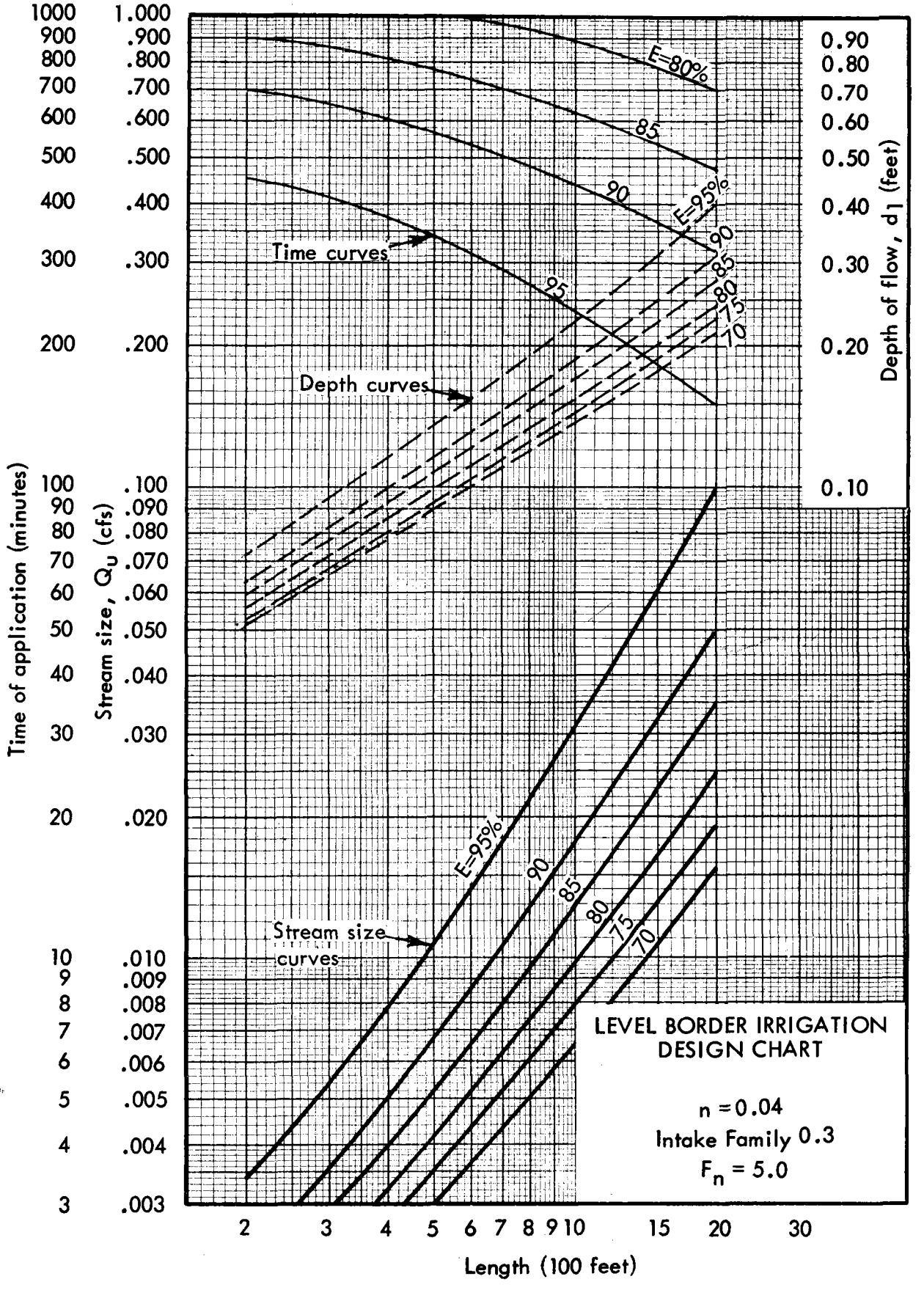
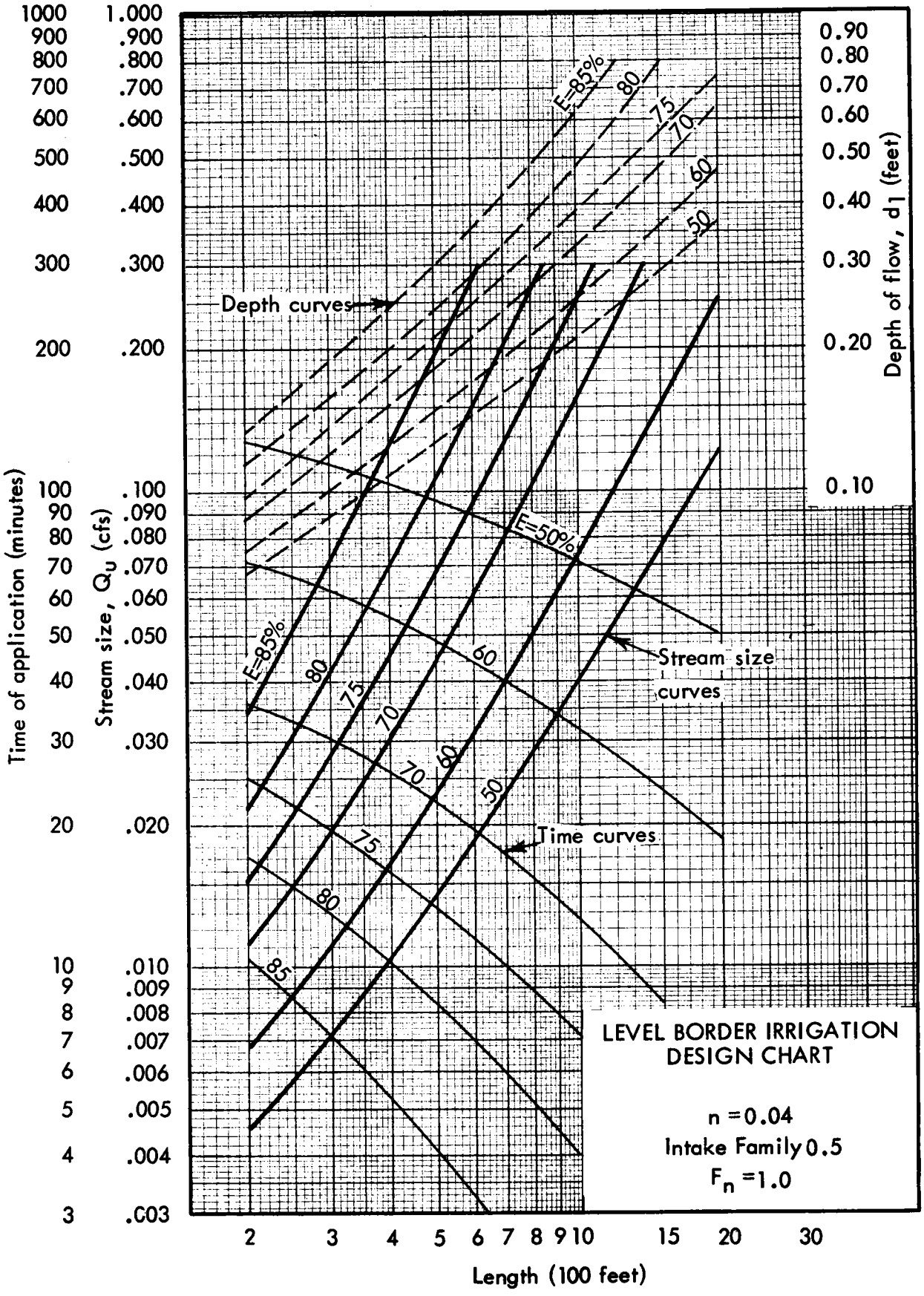
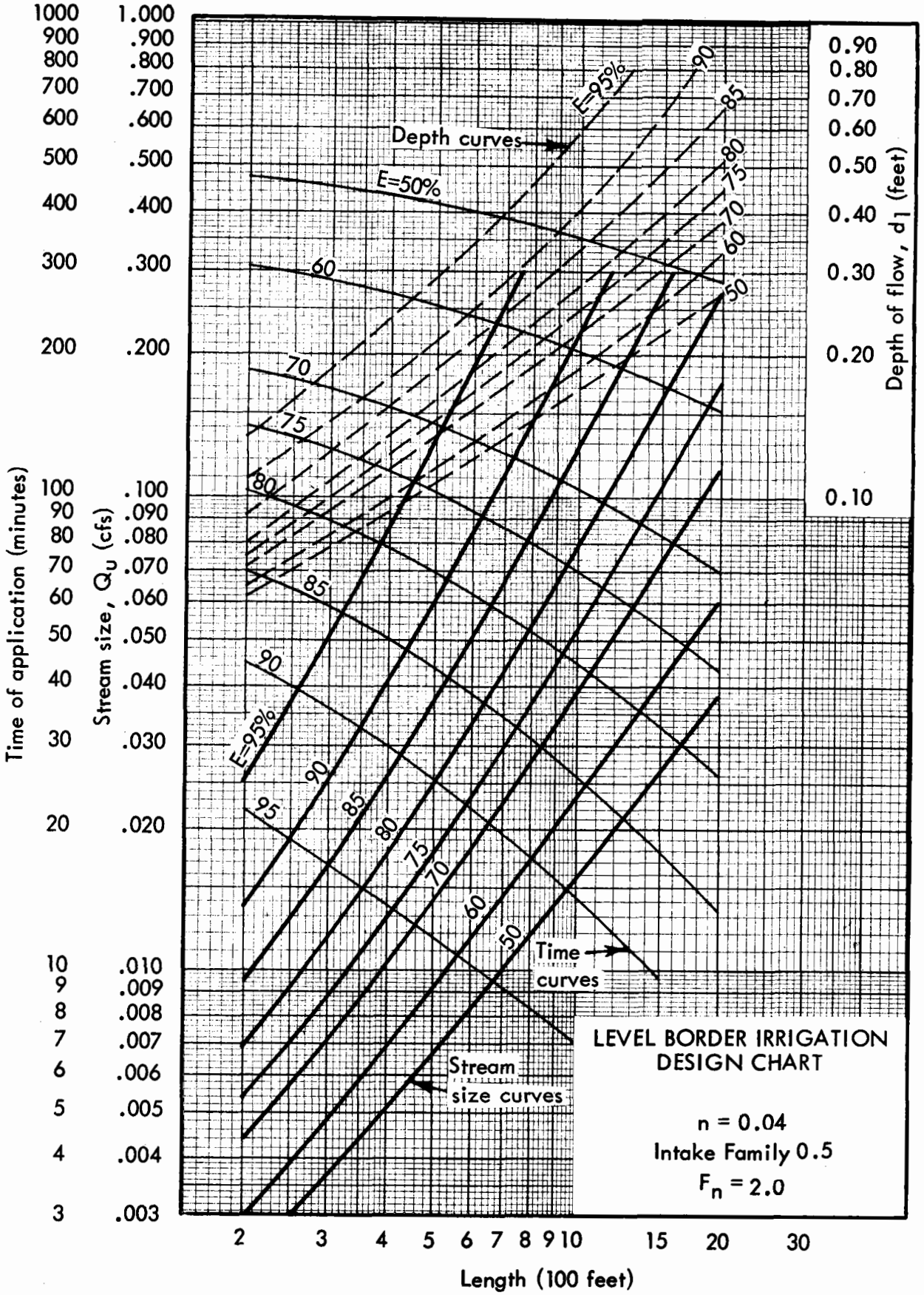
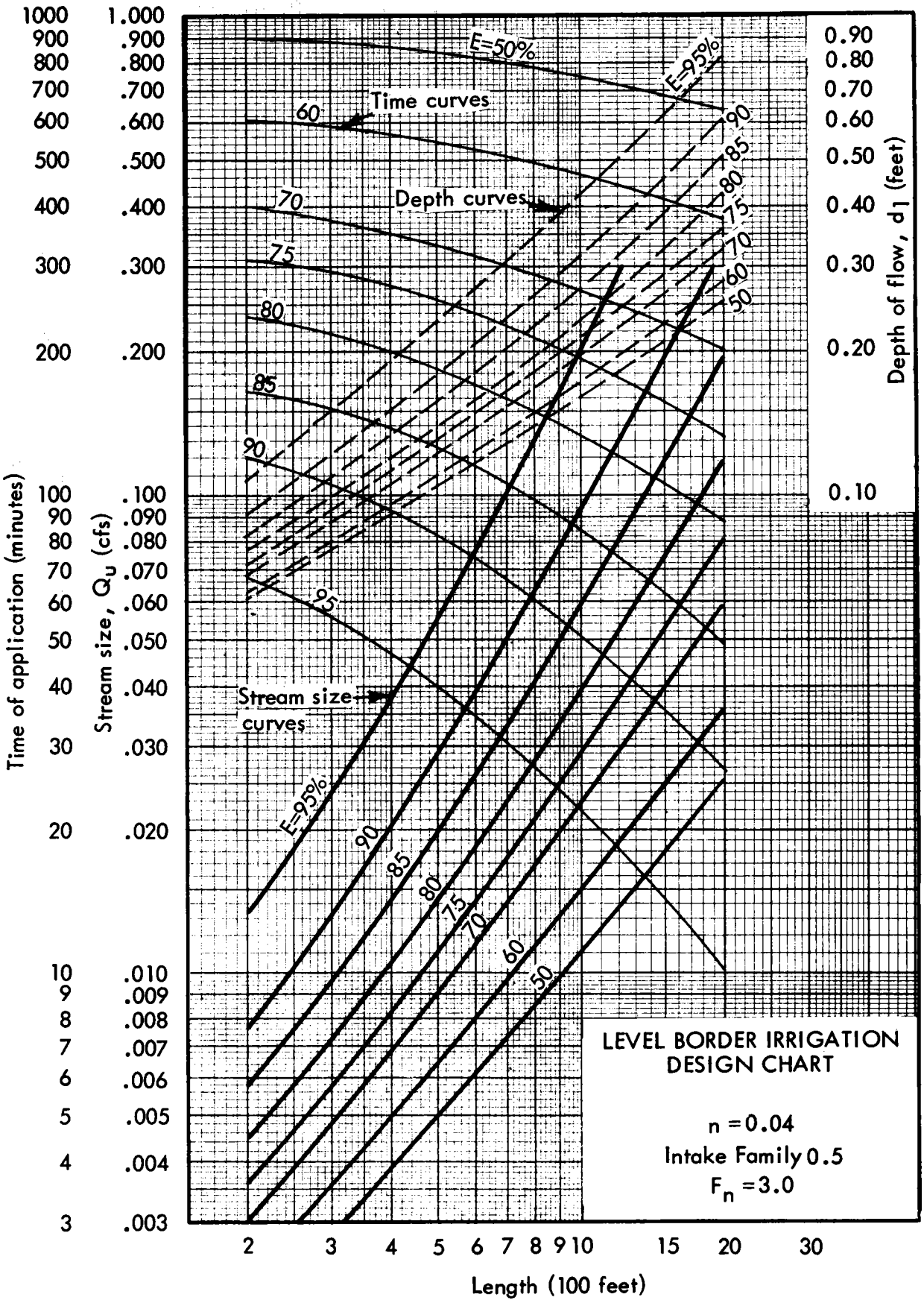
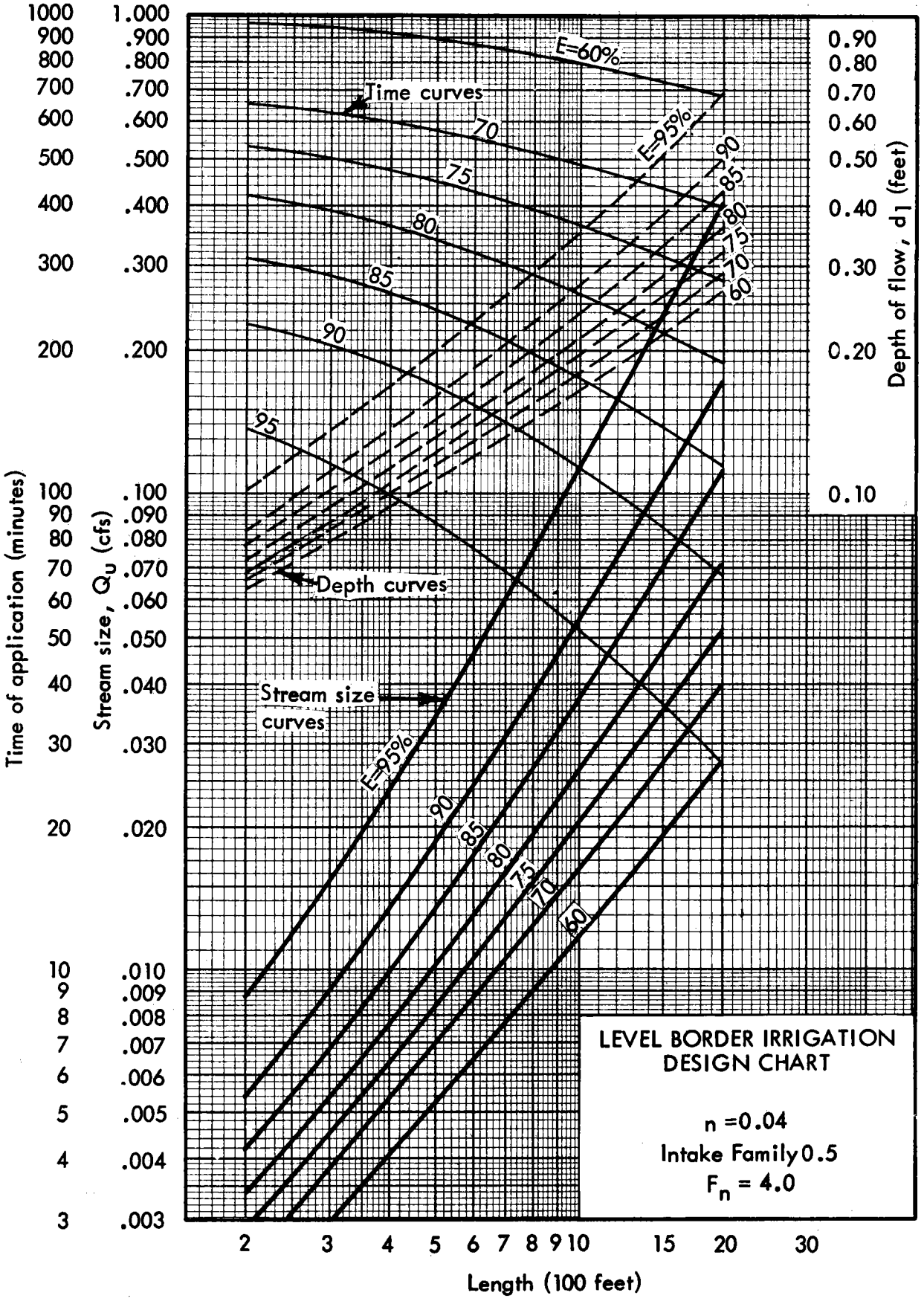
Intake Family 0.3
F_n = 4.0

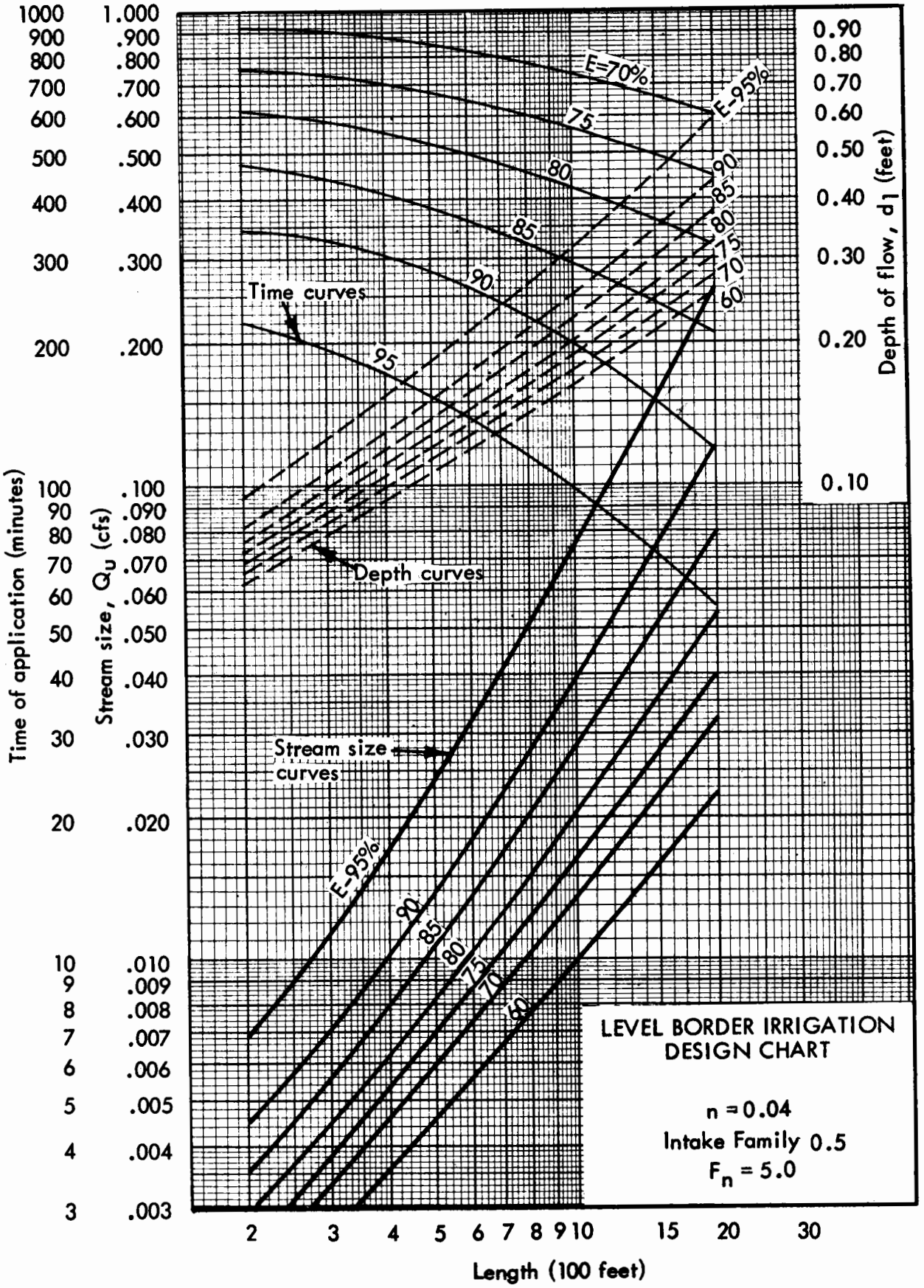

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=80%
85
90
95
E=95%
90
85
80
75
70
E=95%
90
85
80
75
70
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.3
F_n = 5.0

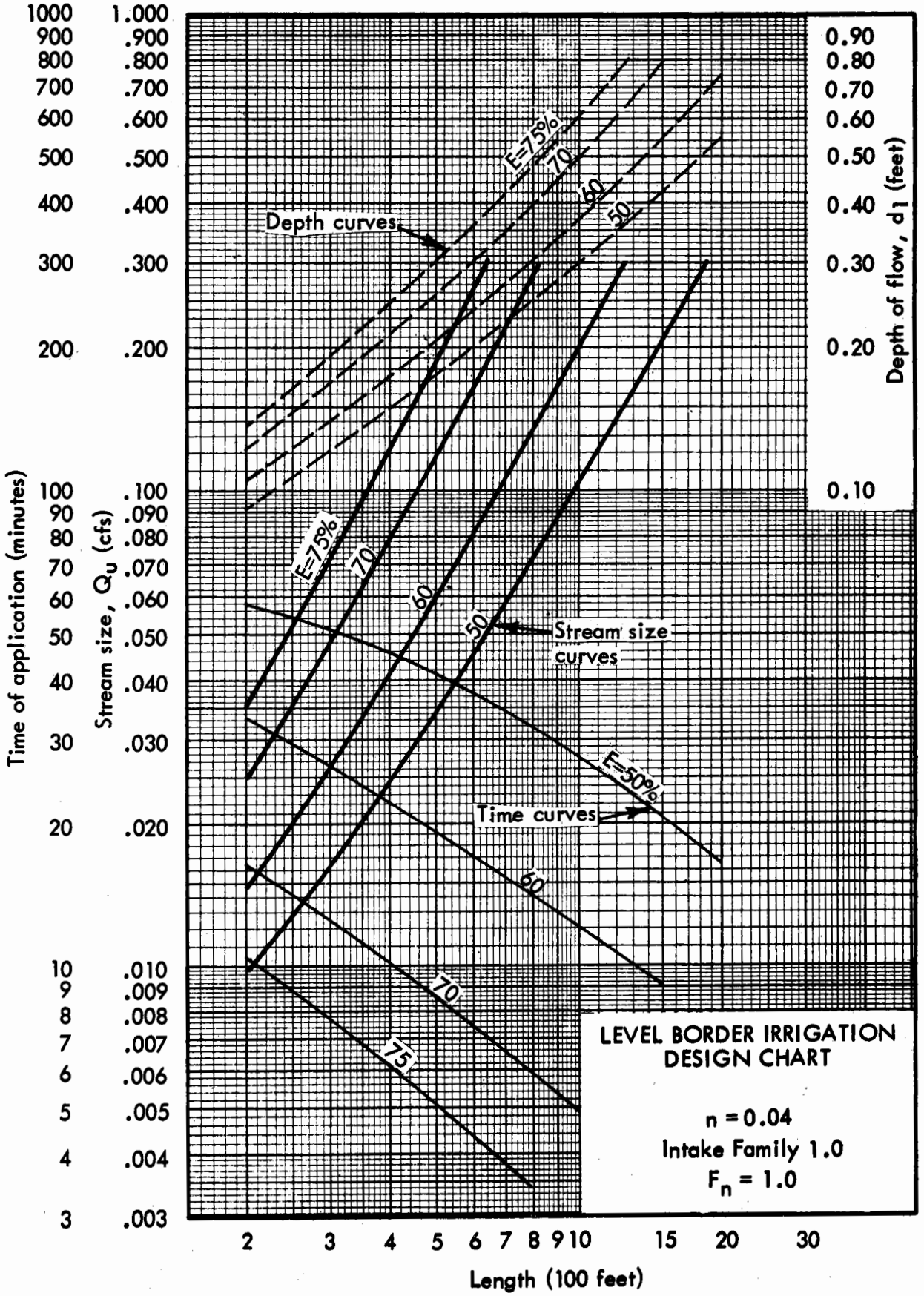

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 1.0

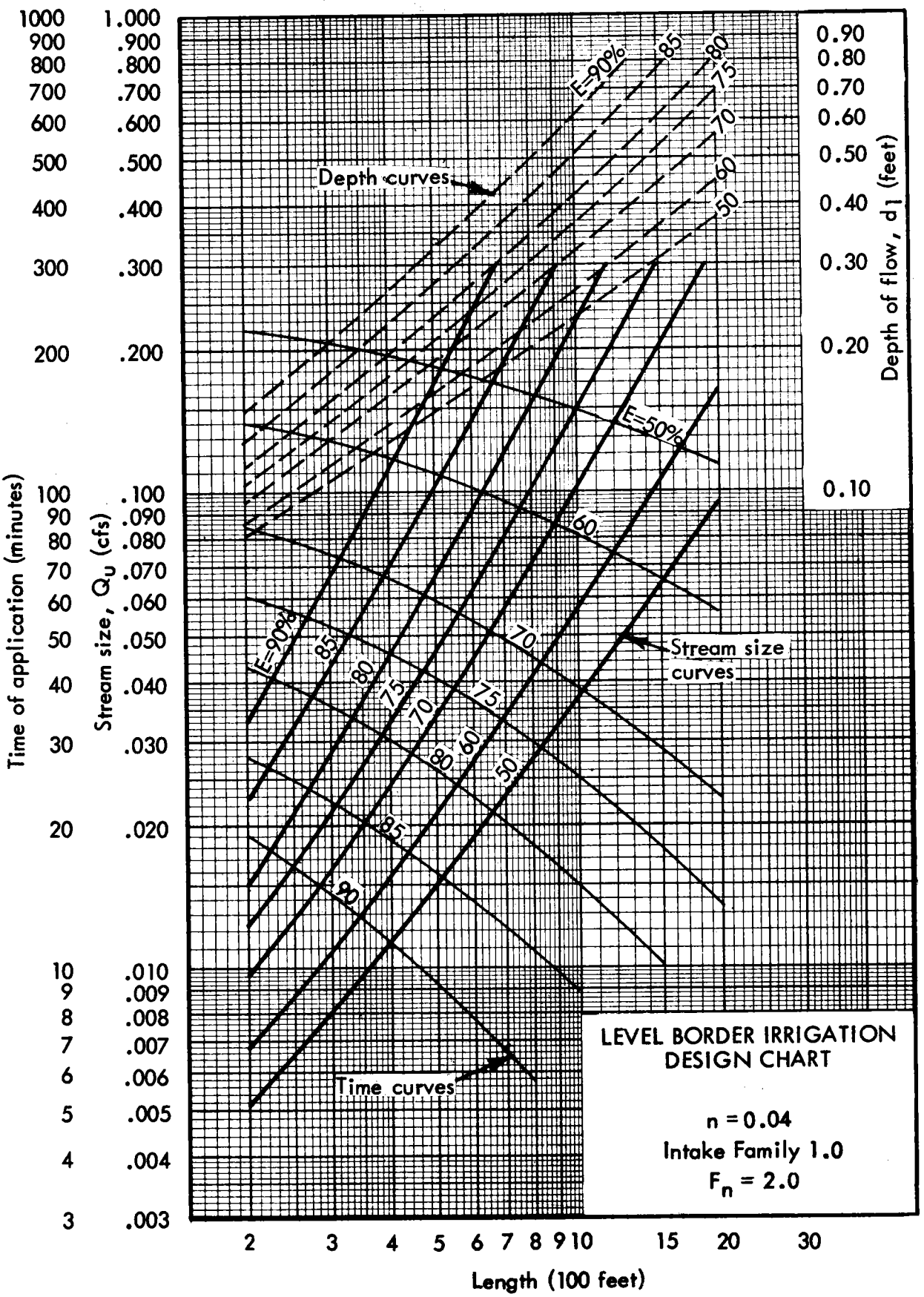

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 2.0

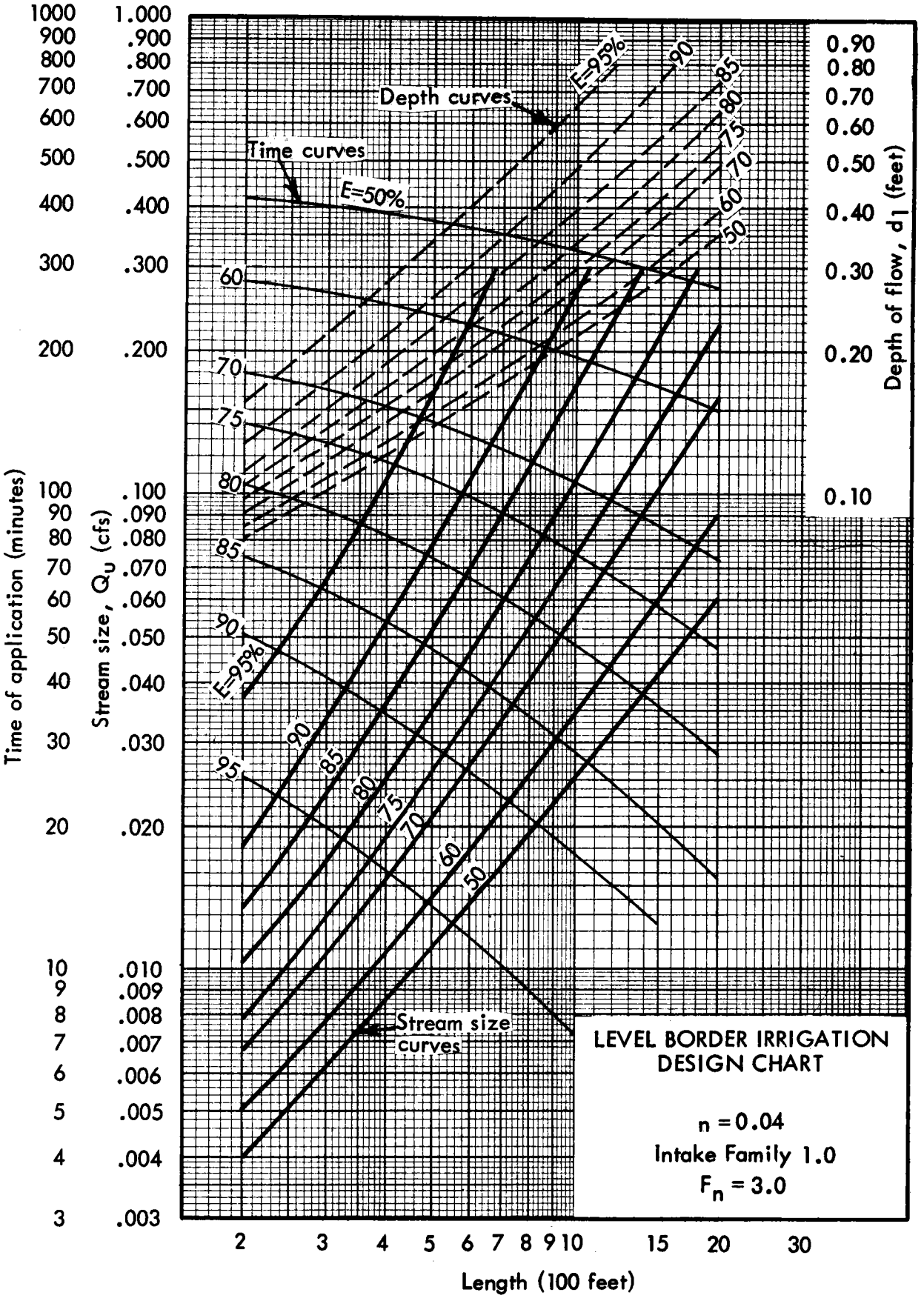

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=50%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 3.0

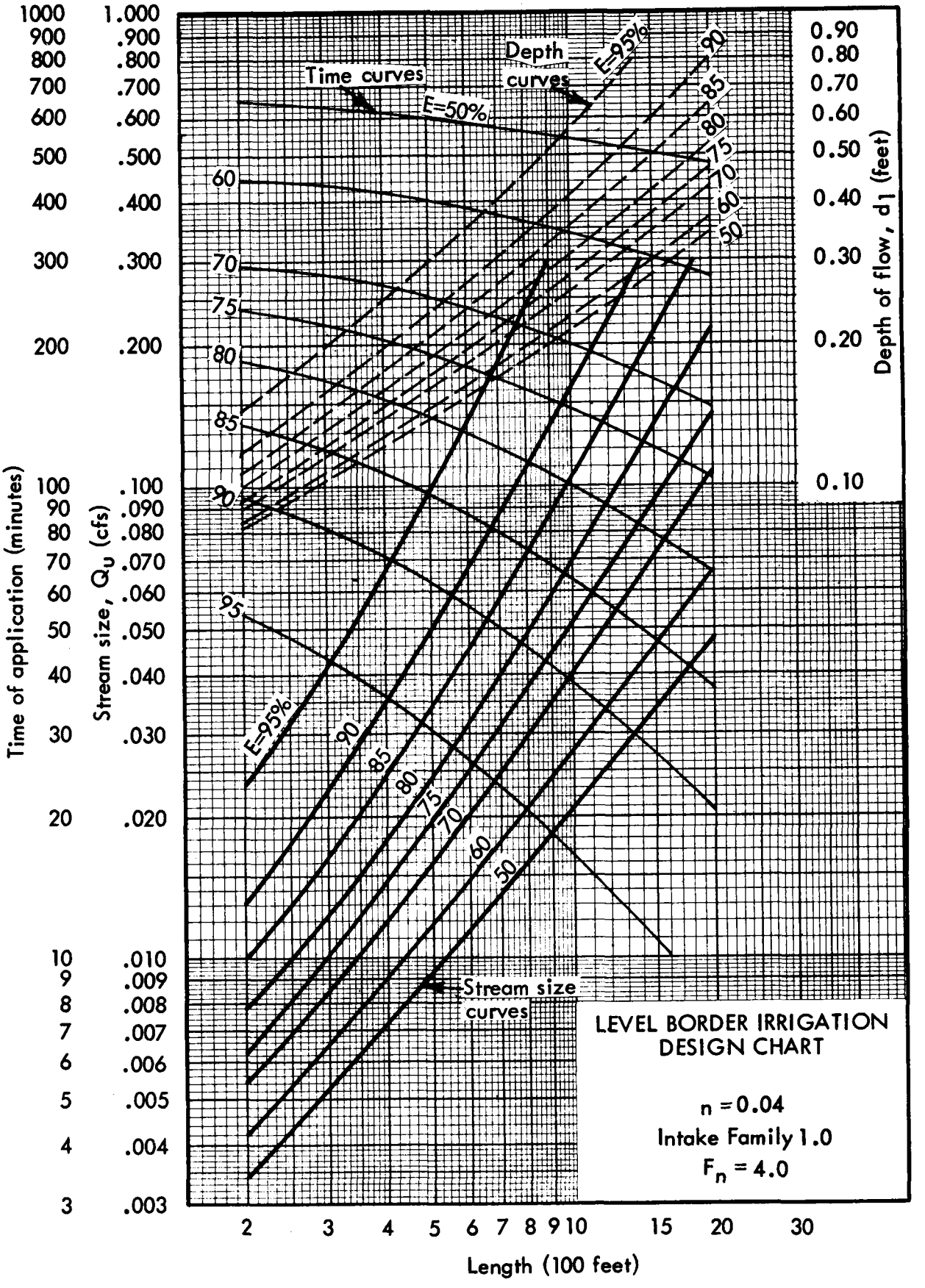

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=60%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n =0.04
Intake Family 0.5
F_n = 4.0

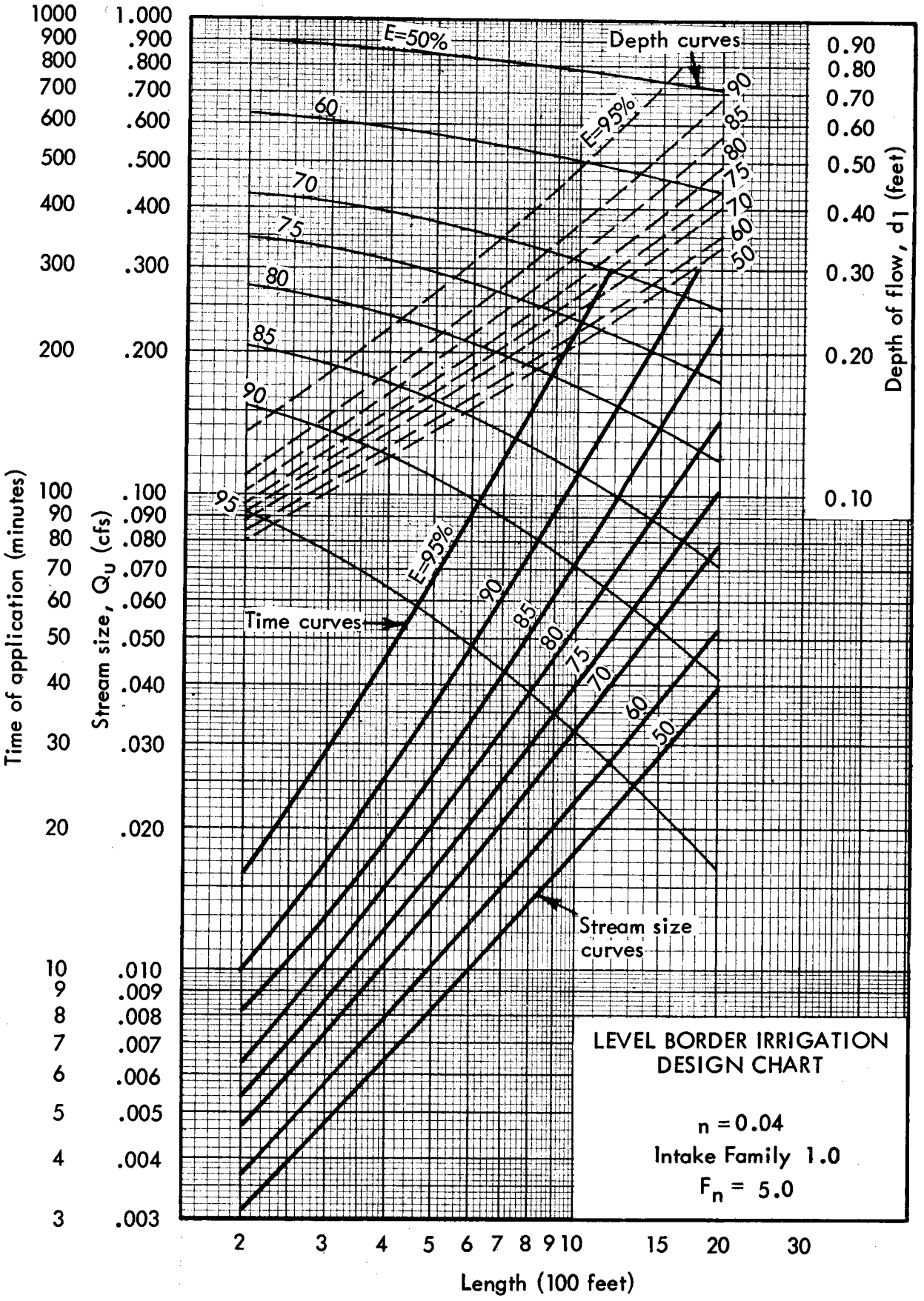

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 5.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=70%
E=95%
75
80
85
90
95
60
70

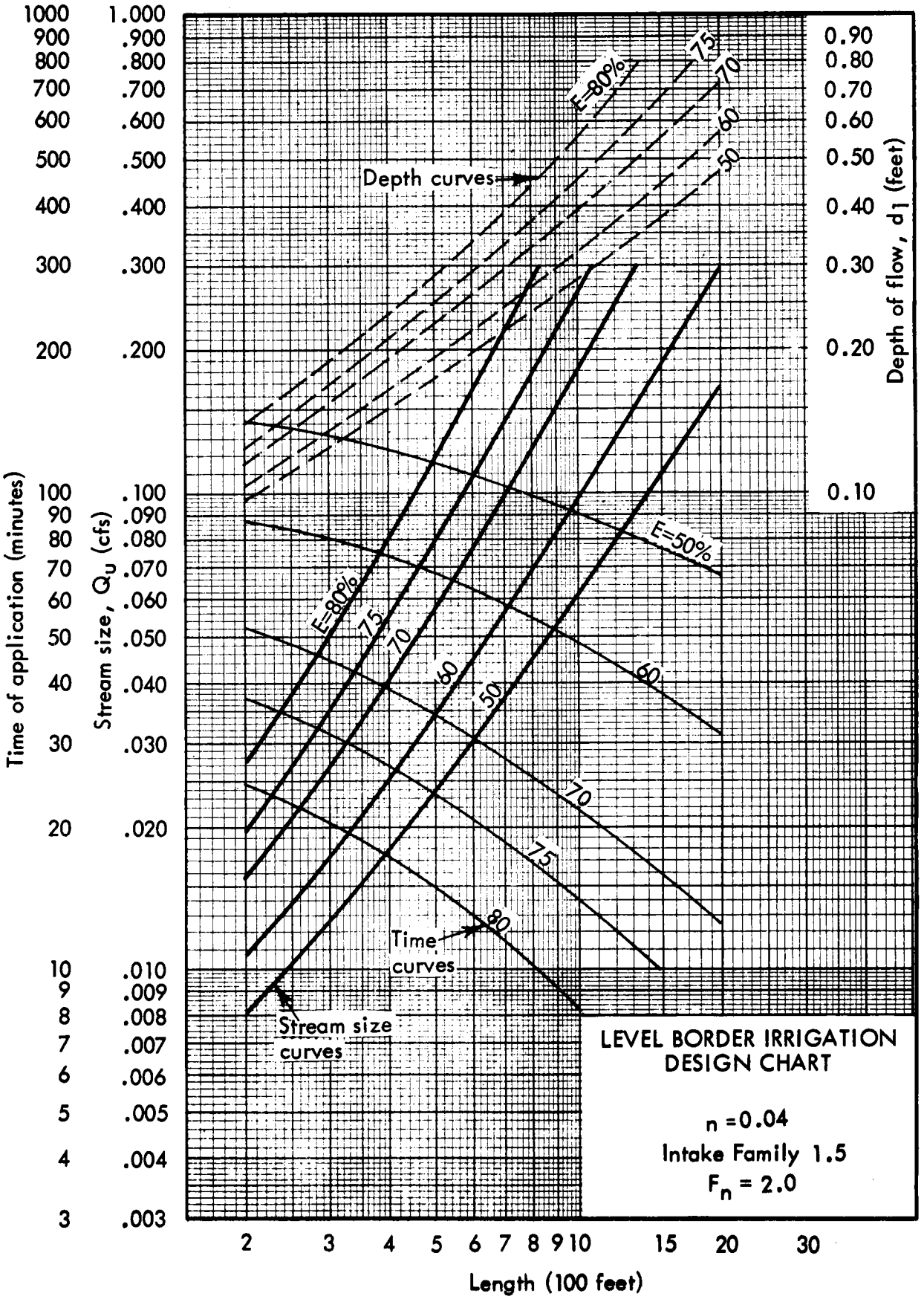

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=75%
70
60
50
E=50%
75
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 1.0

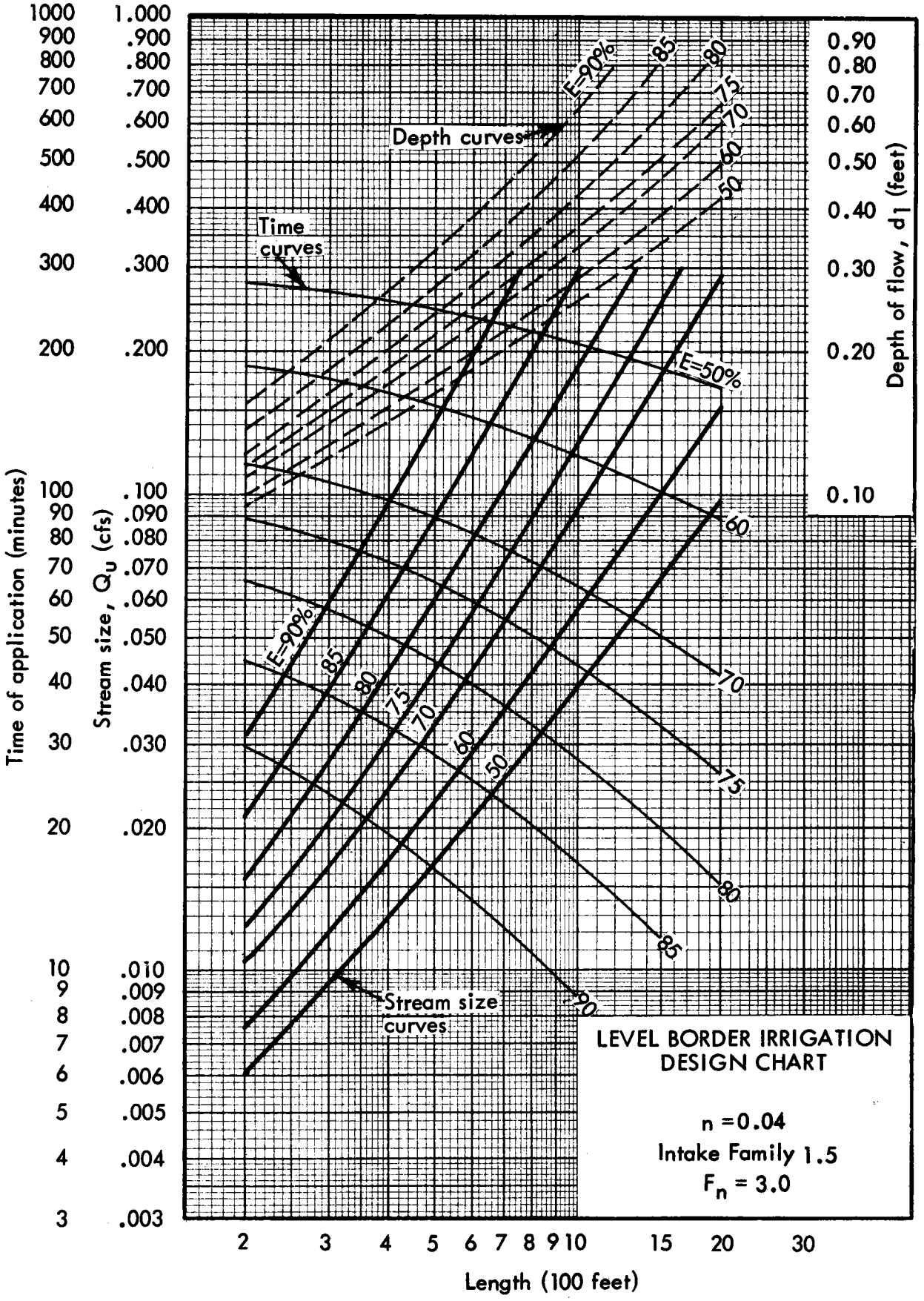

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 2.0
Depth curves
Stream size curves
Time curves
E=90%
E=50%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)

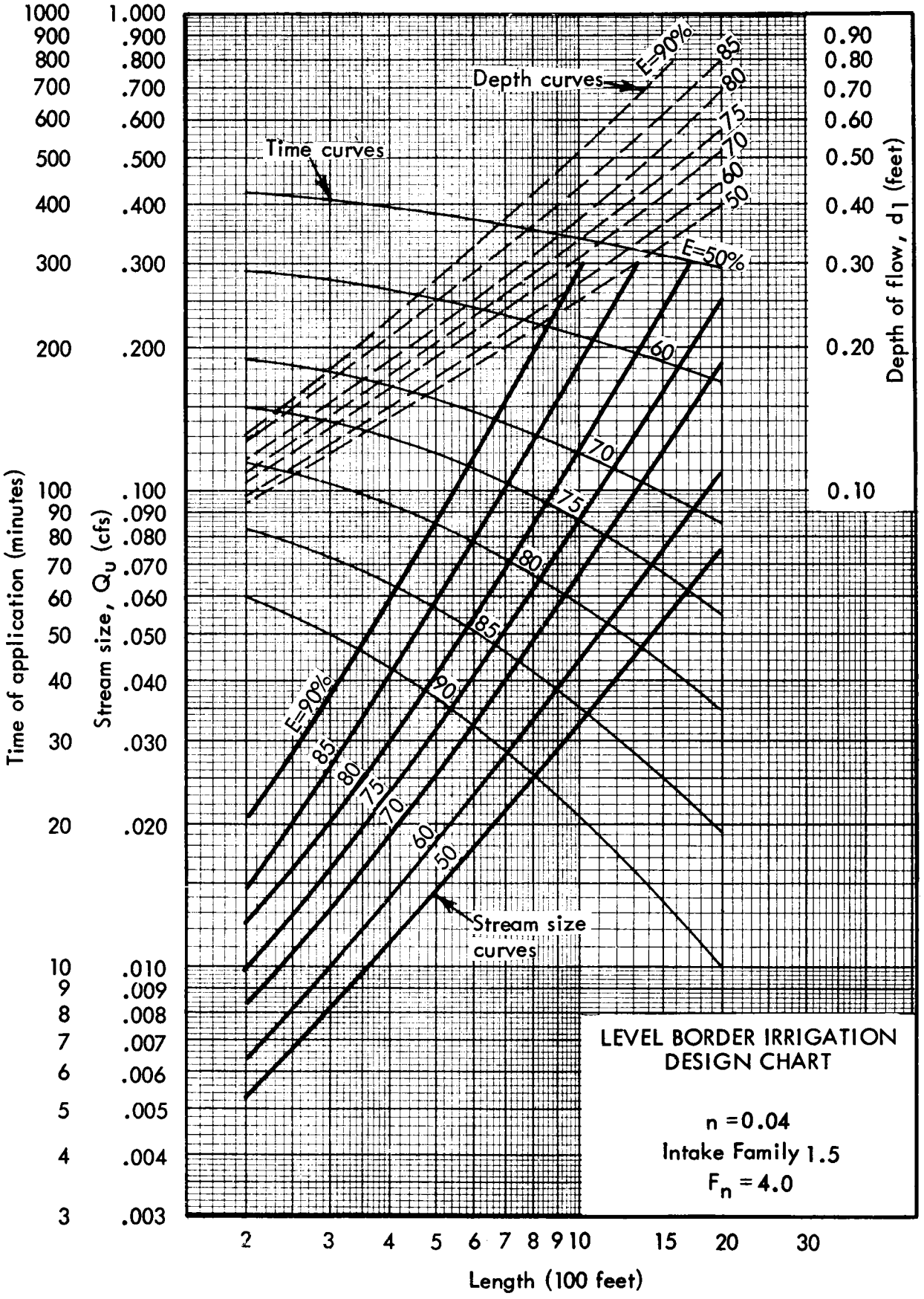

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 3.0

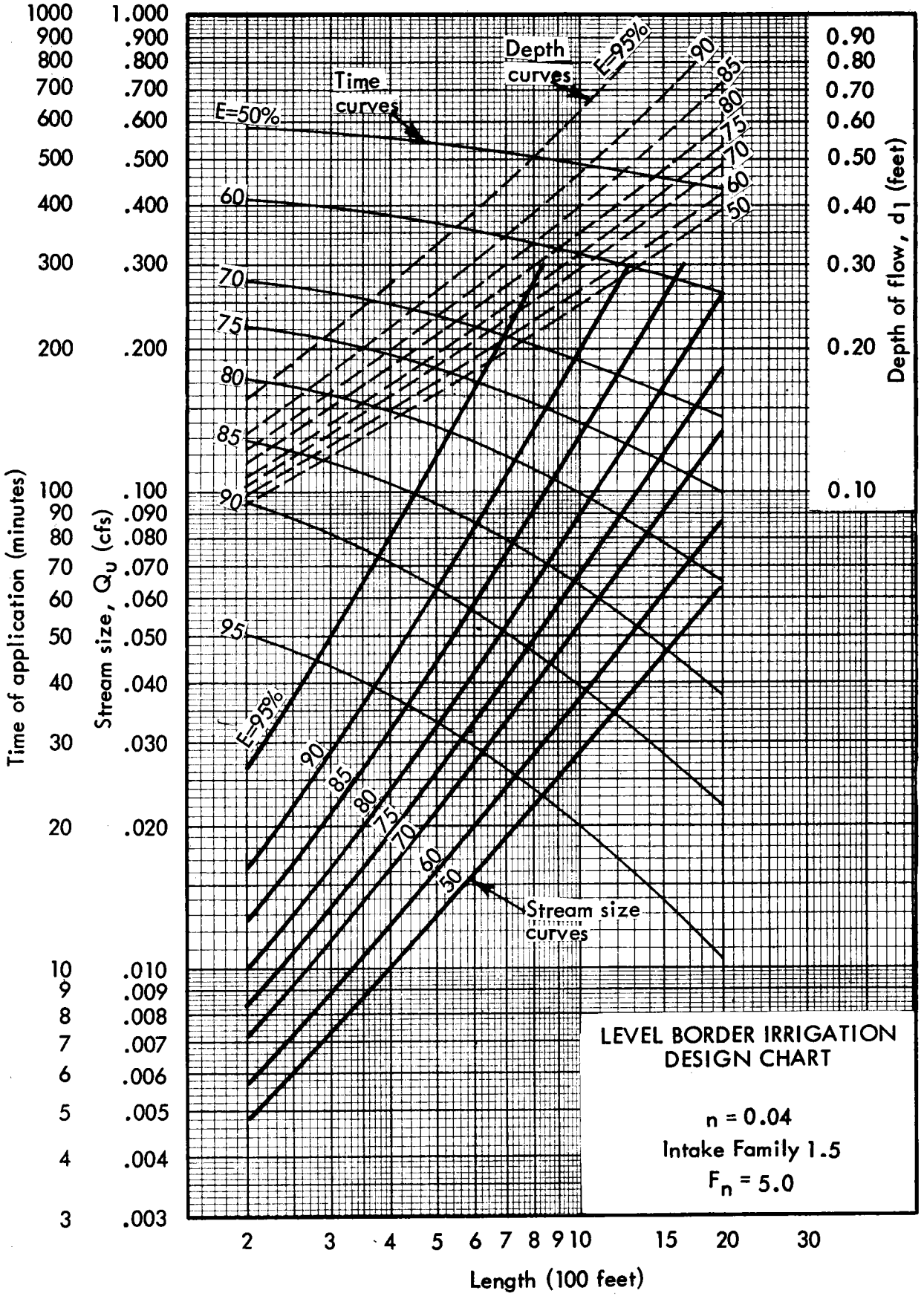

Time curves
Depth curves
Stream size curves
E=50%
E=95%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 4.0

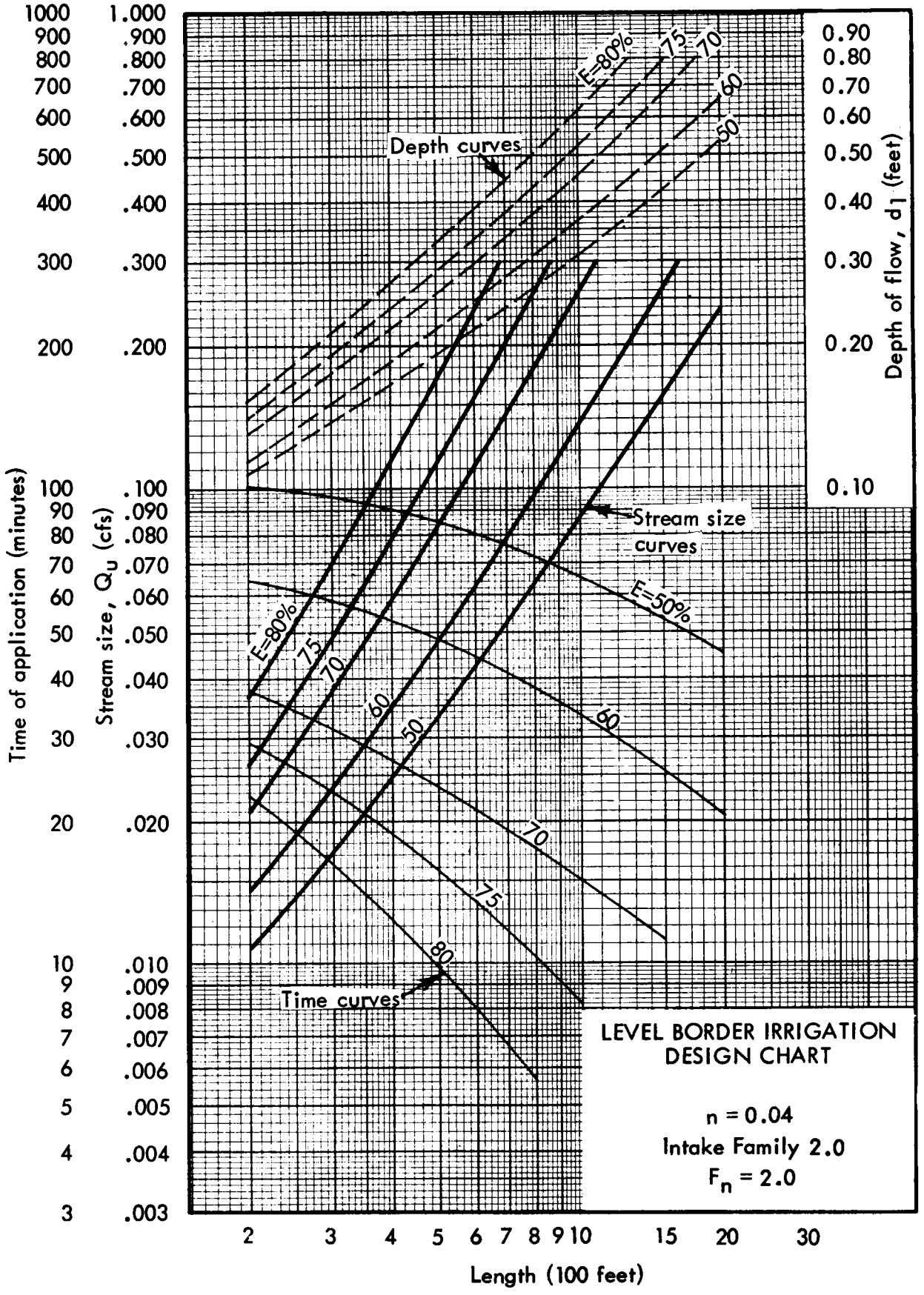

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=50%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 5.0

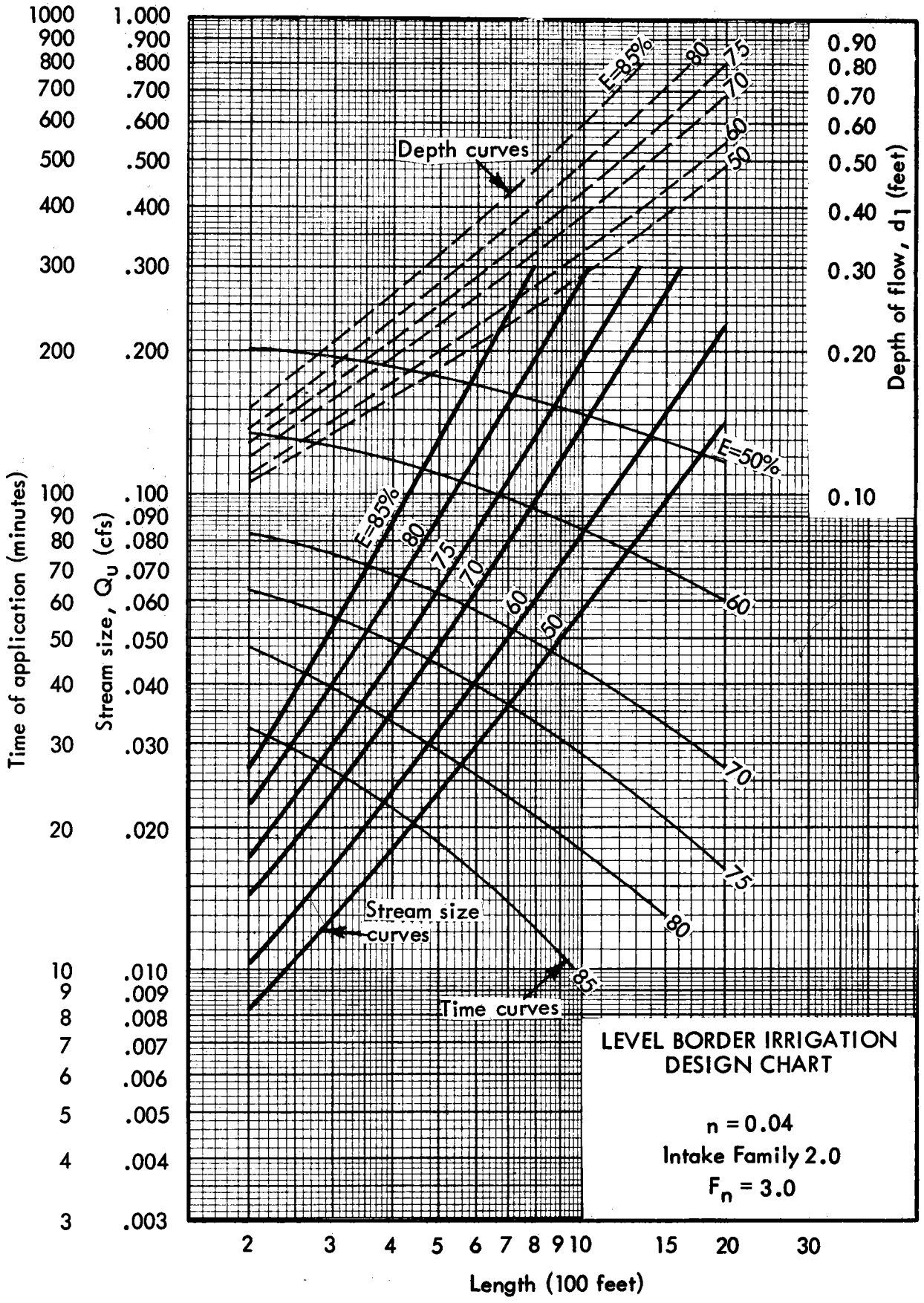

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=80%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 2.0

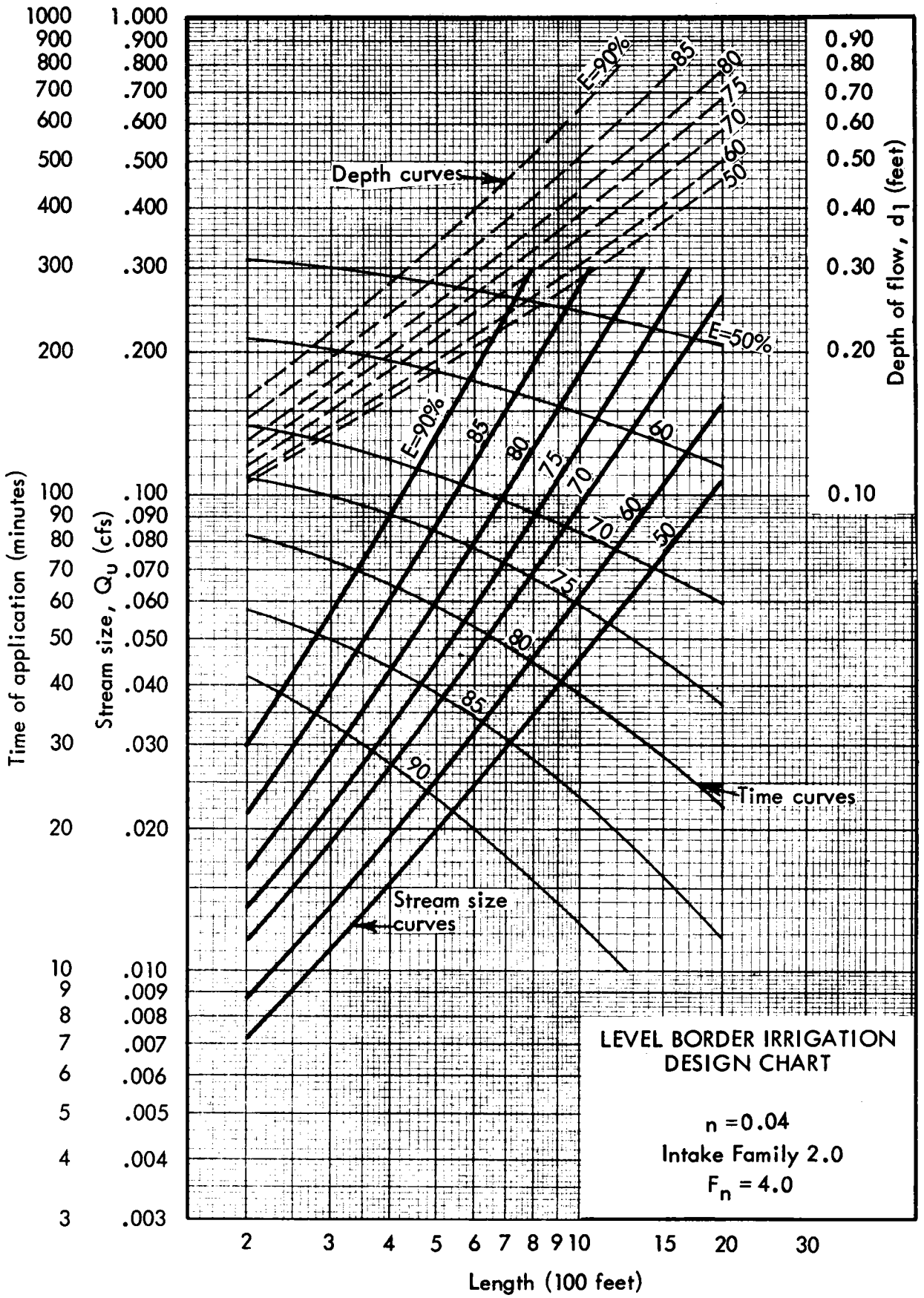

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
85
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 3.0

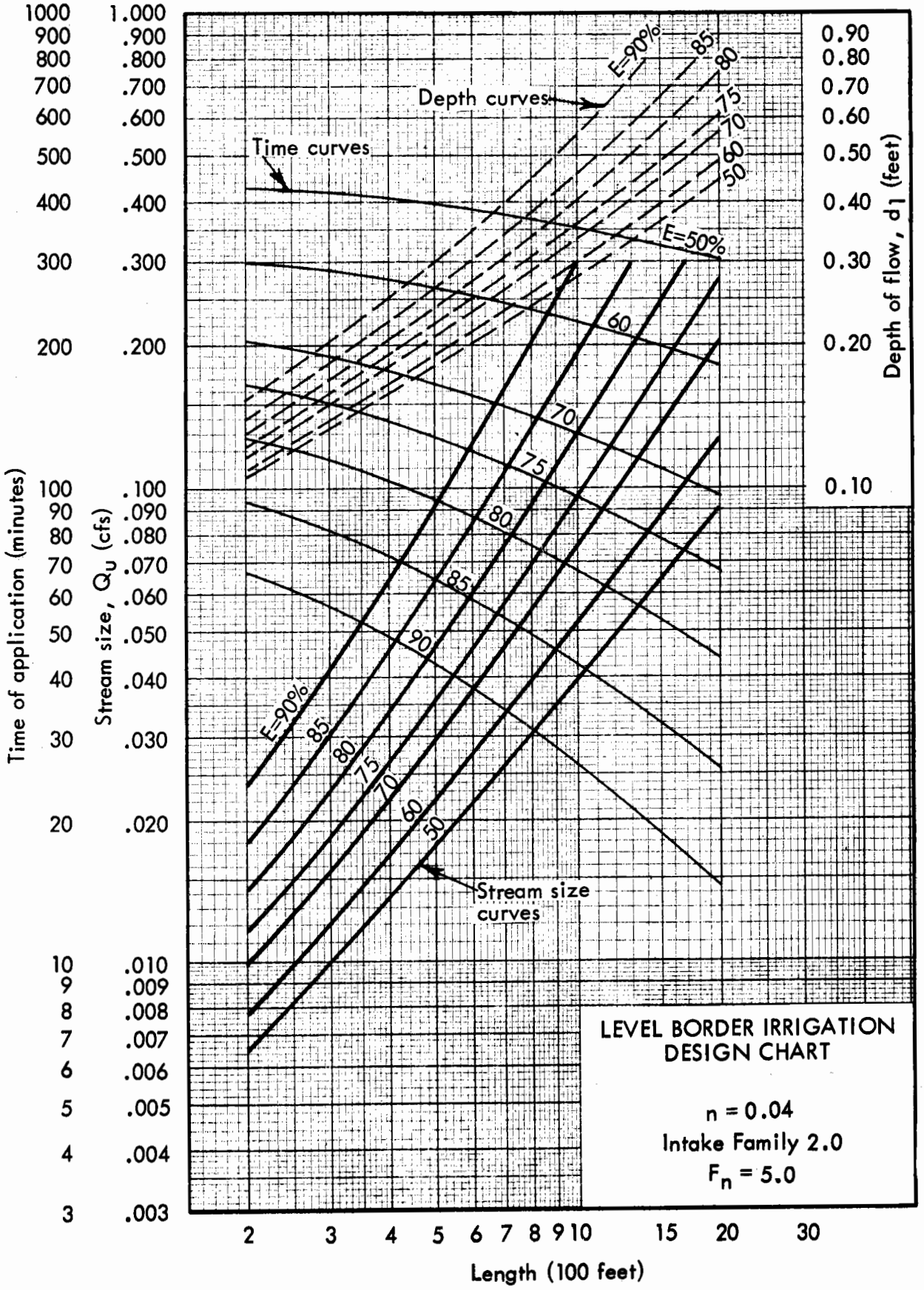

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 4.0

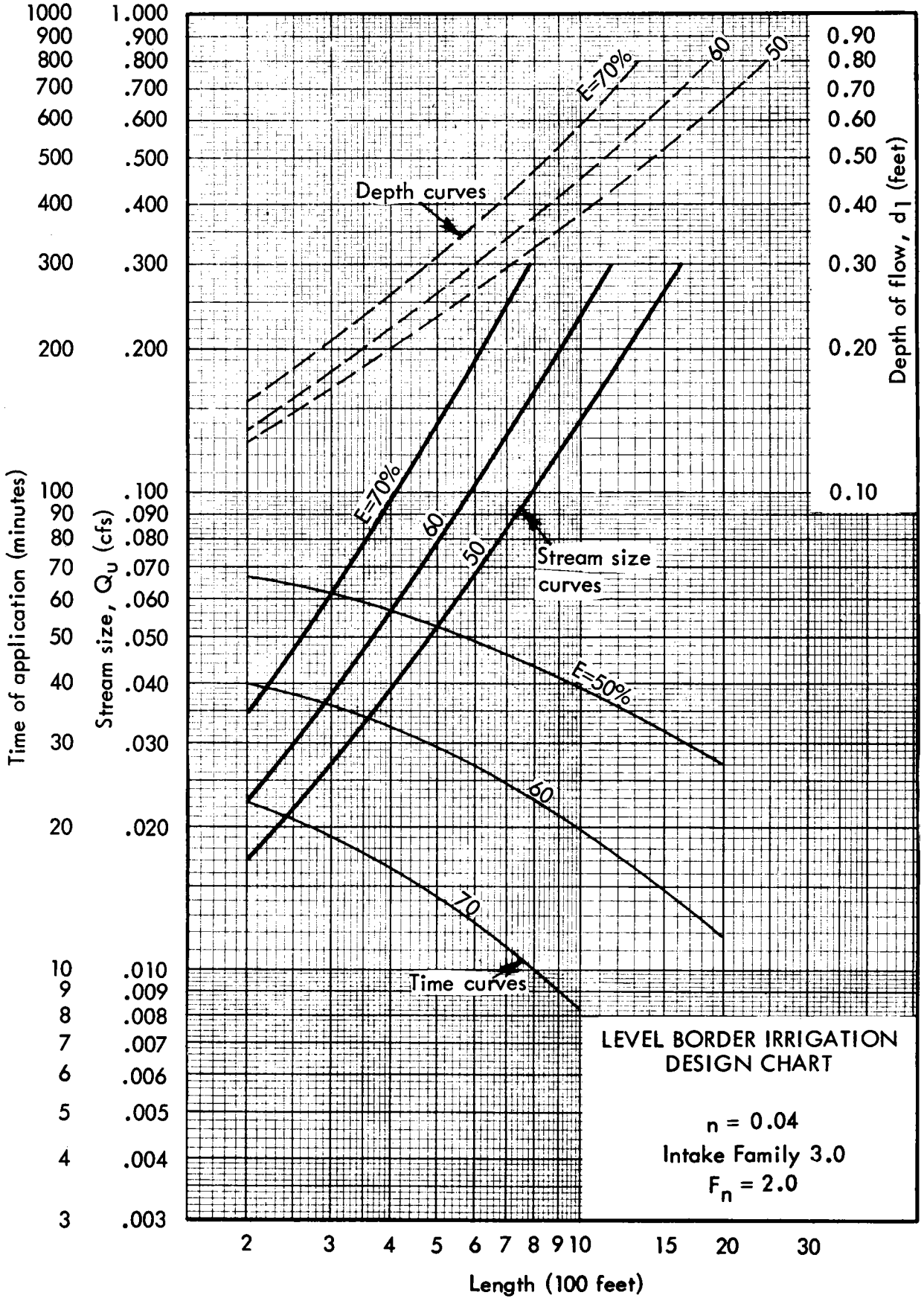

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=50%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 5.0

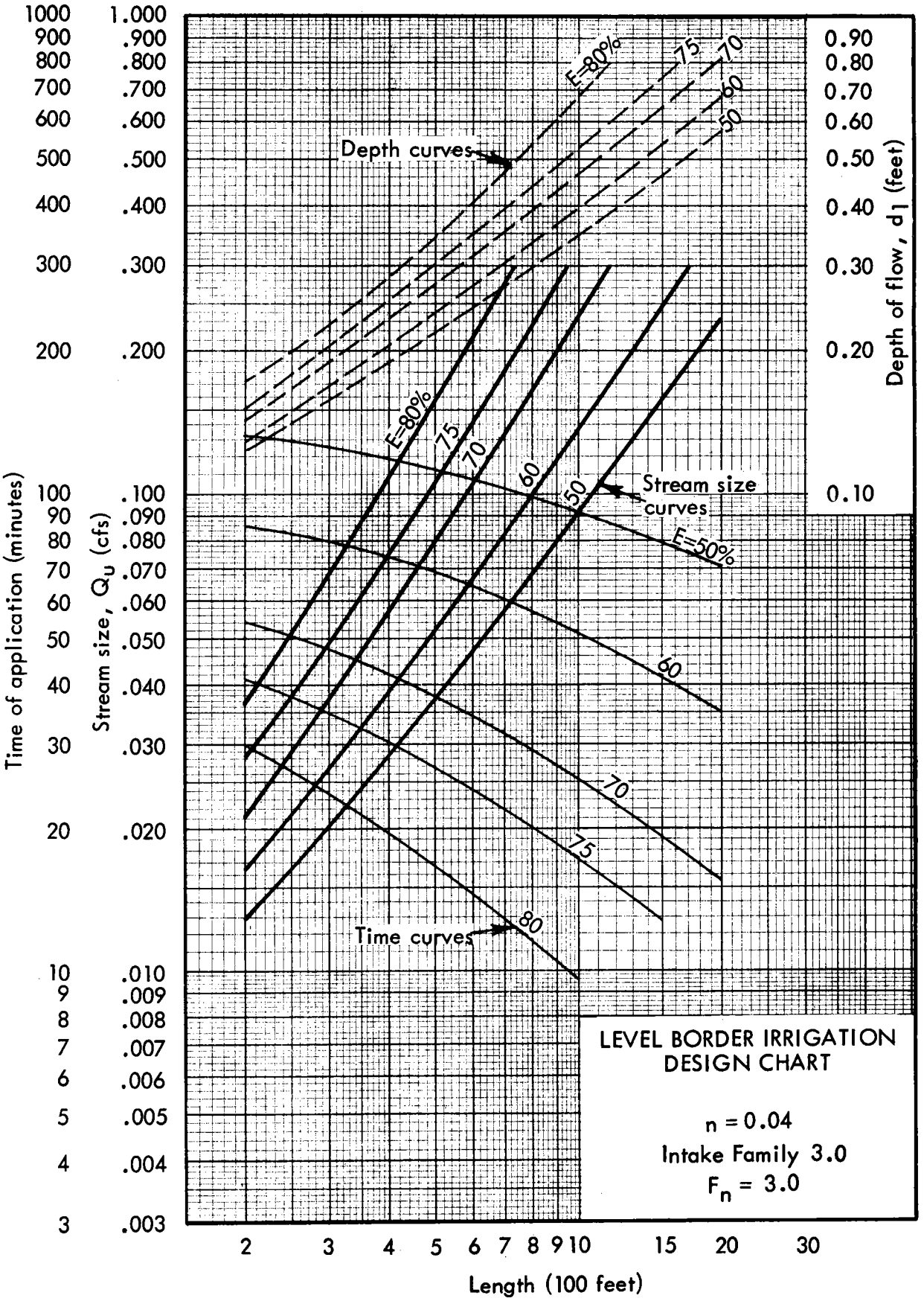

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 2.0

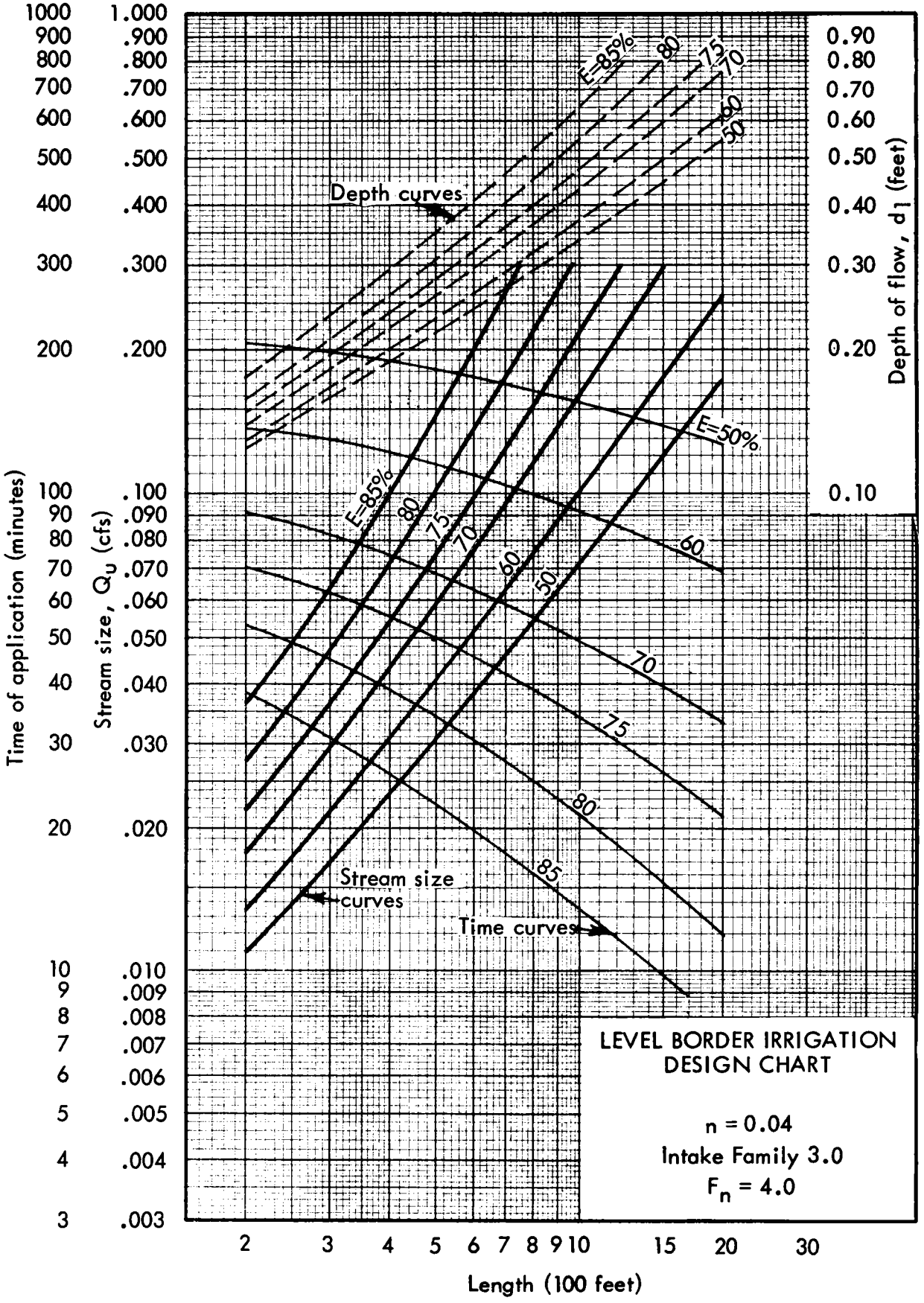

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 3.0

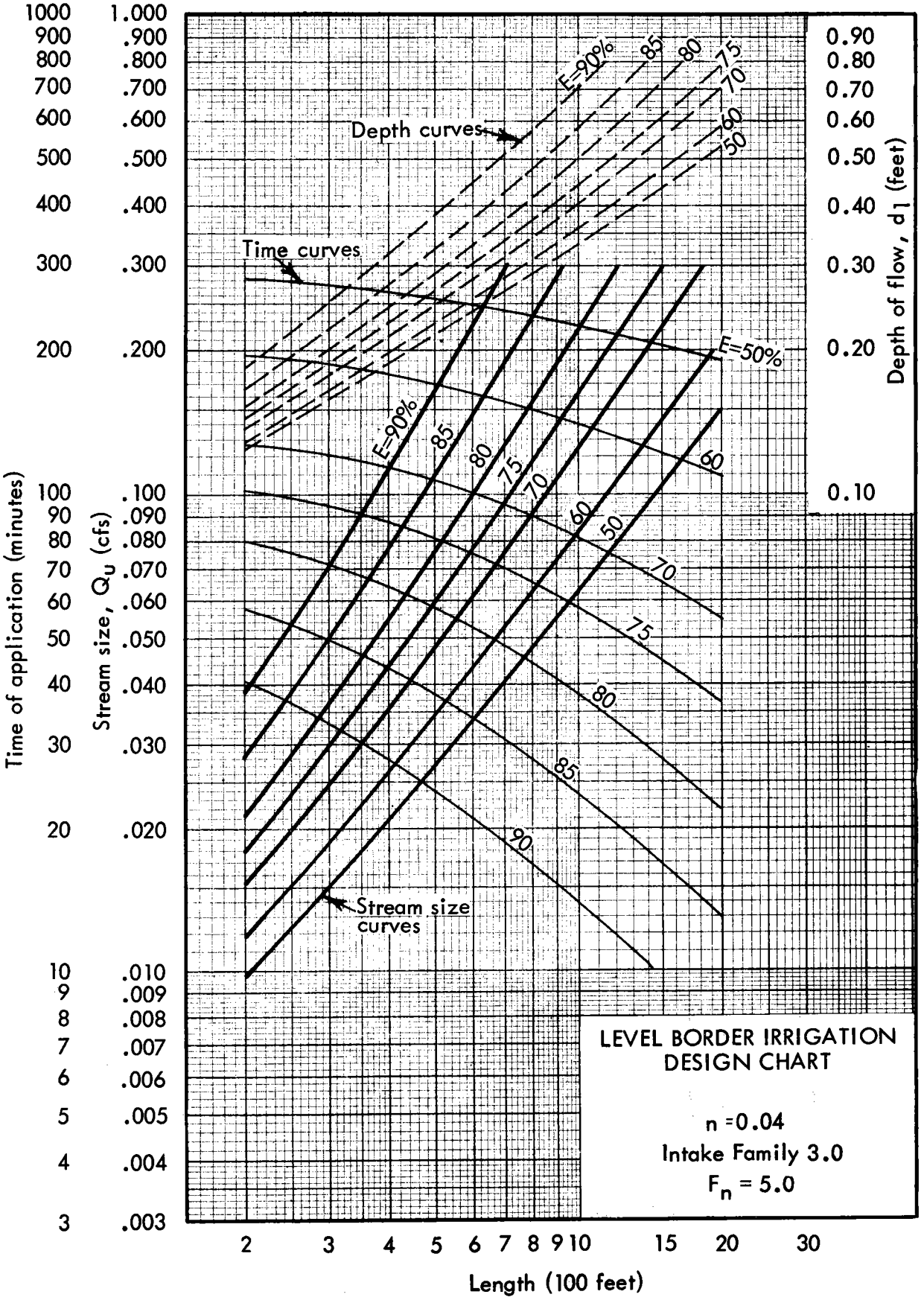

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 4.0

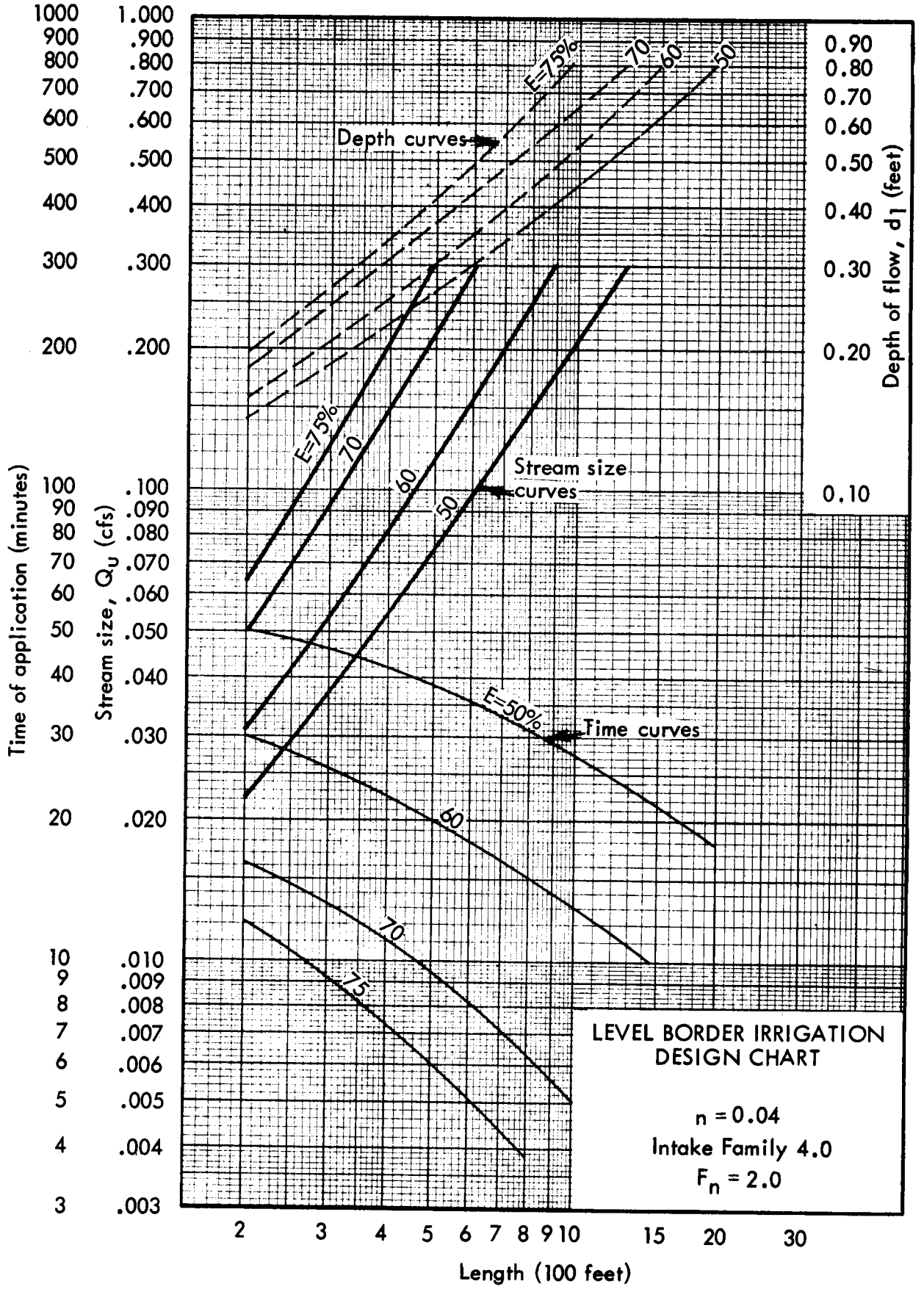

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 5.0

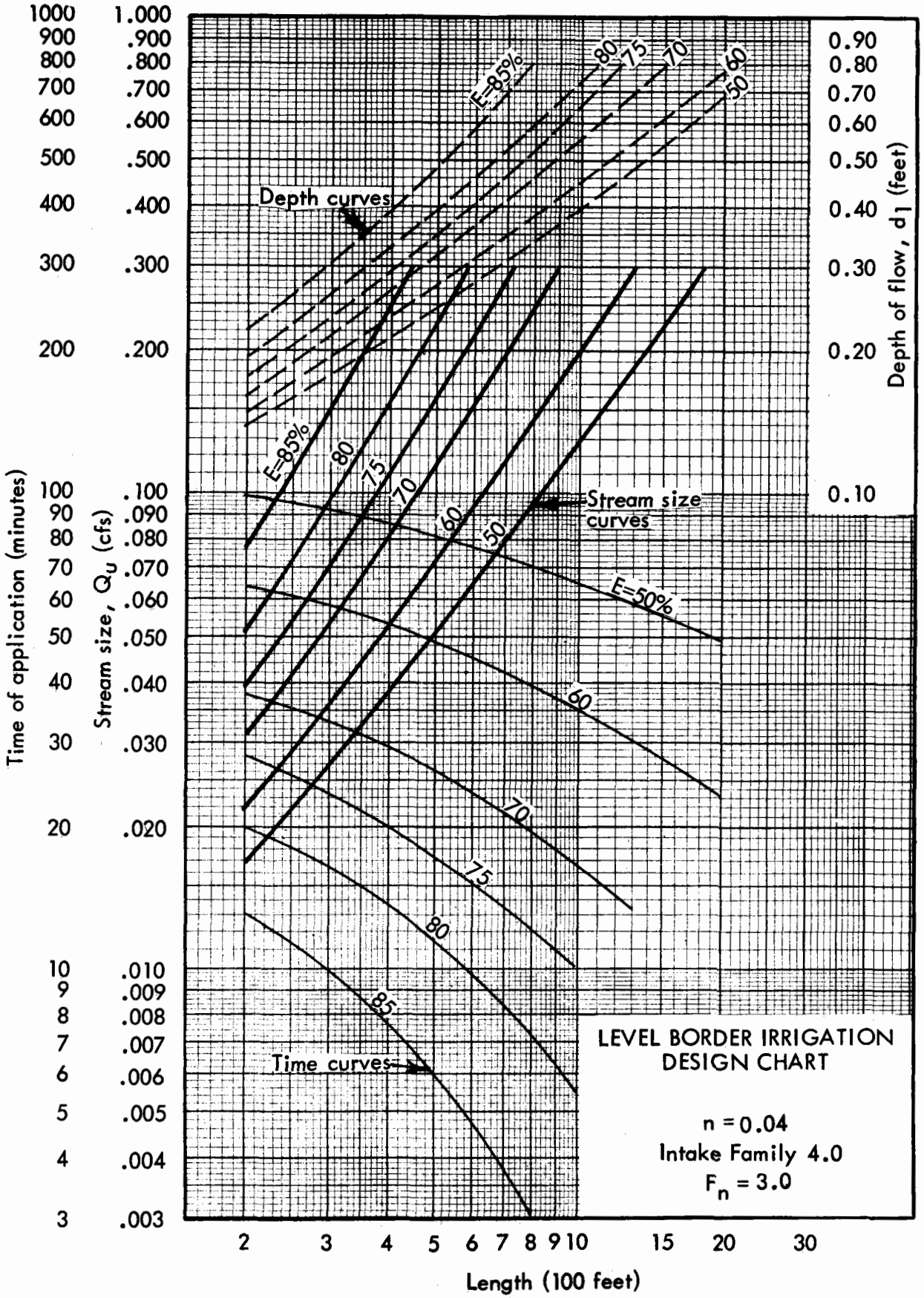

Time of application (minutes)
Stream size, Q_U (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=70%
60
50
E=50%
70
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 2.0

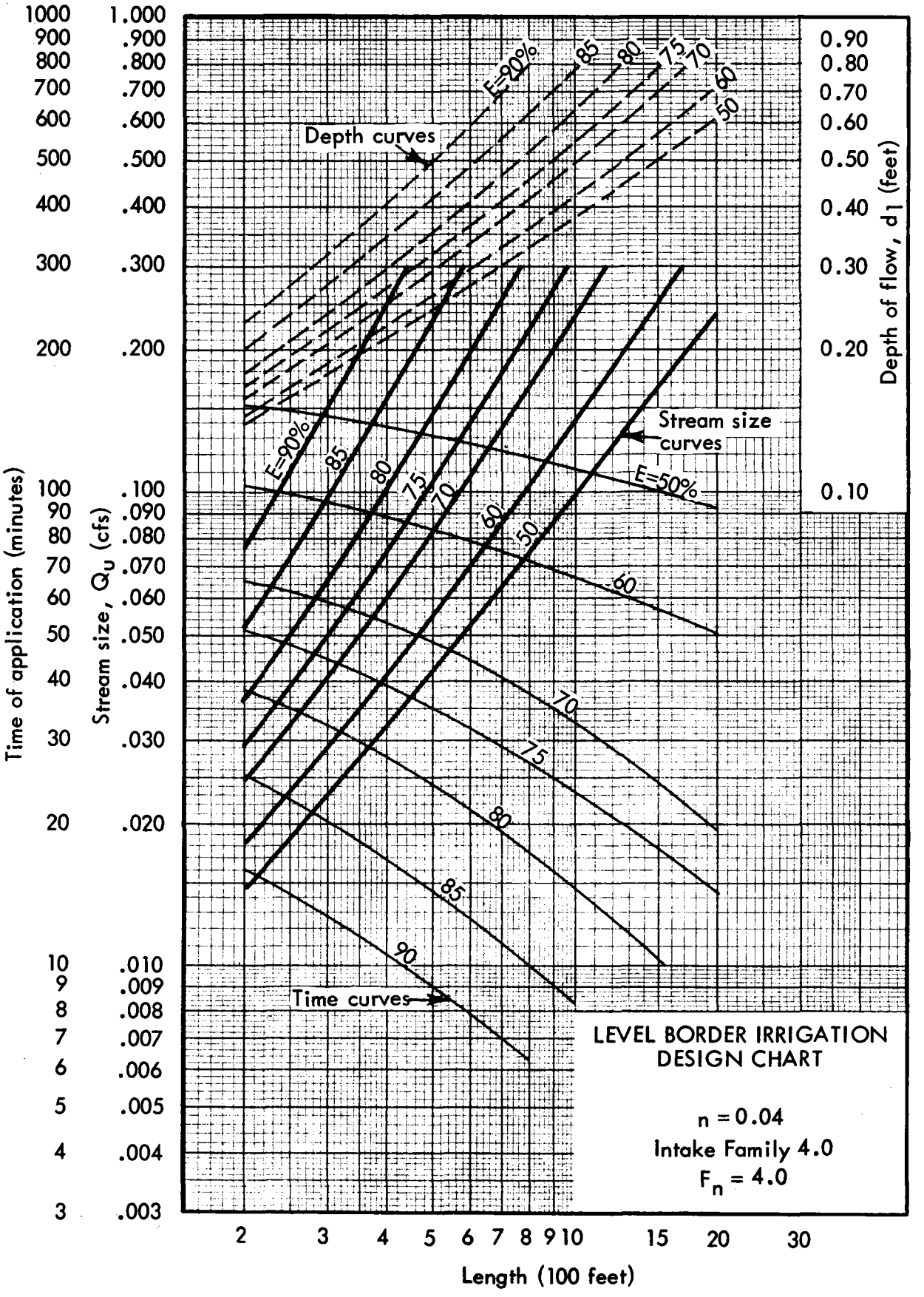

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 3.0

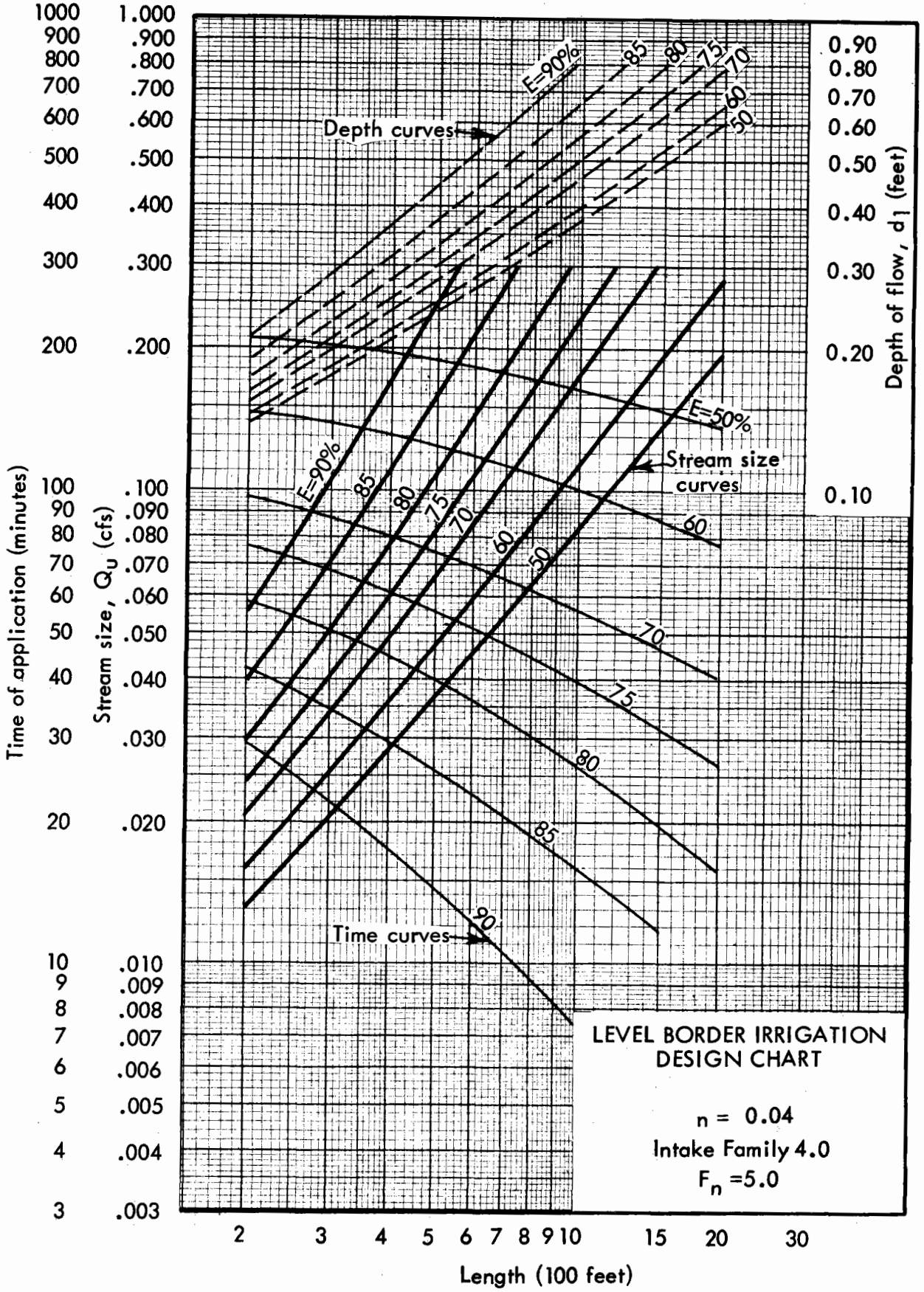

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 4.0

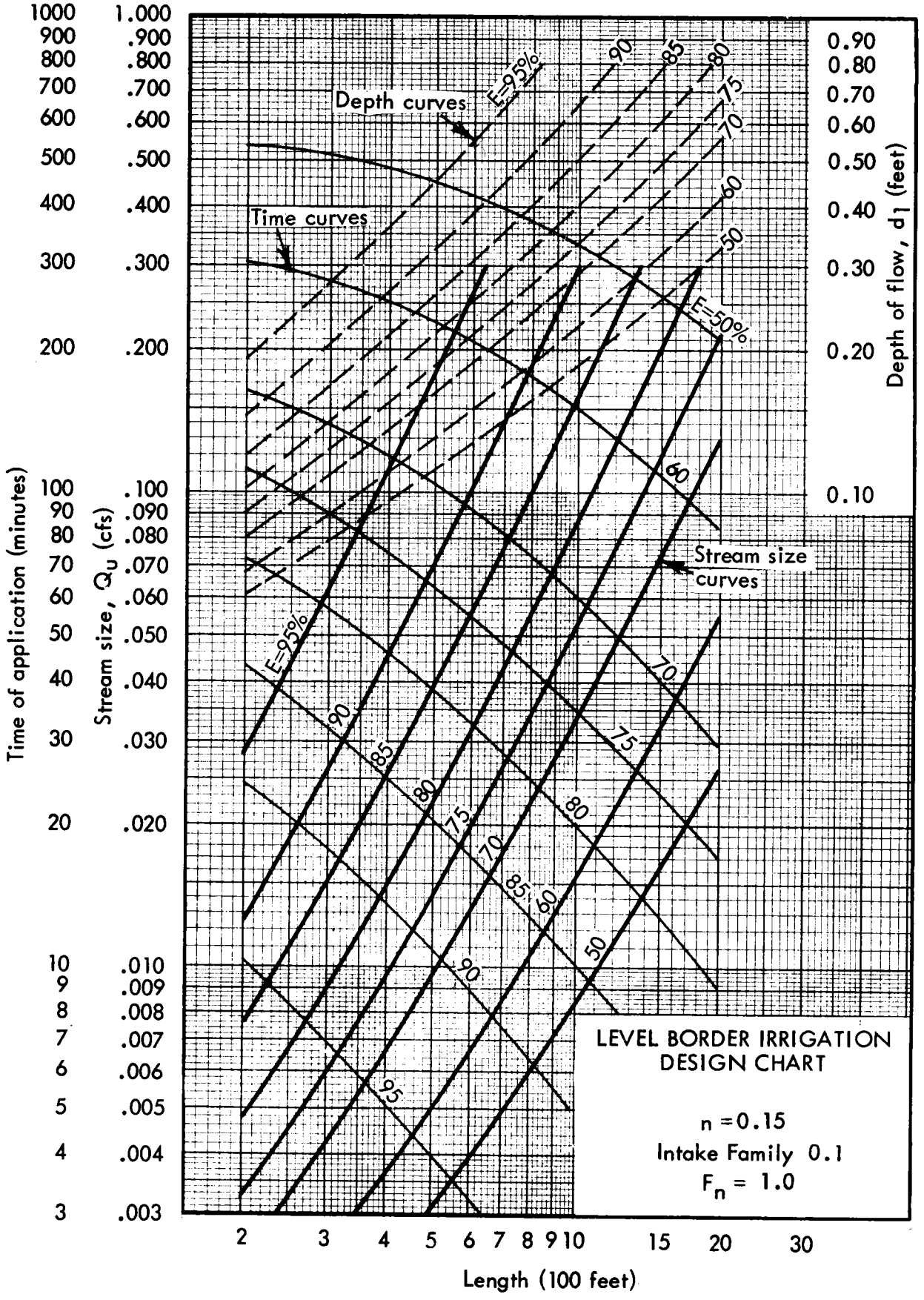

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 5.0

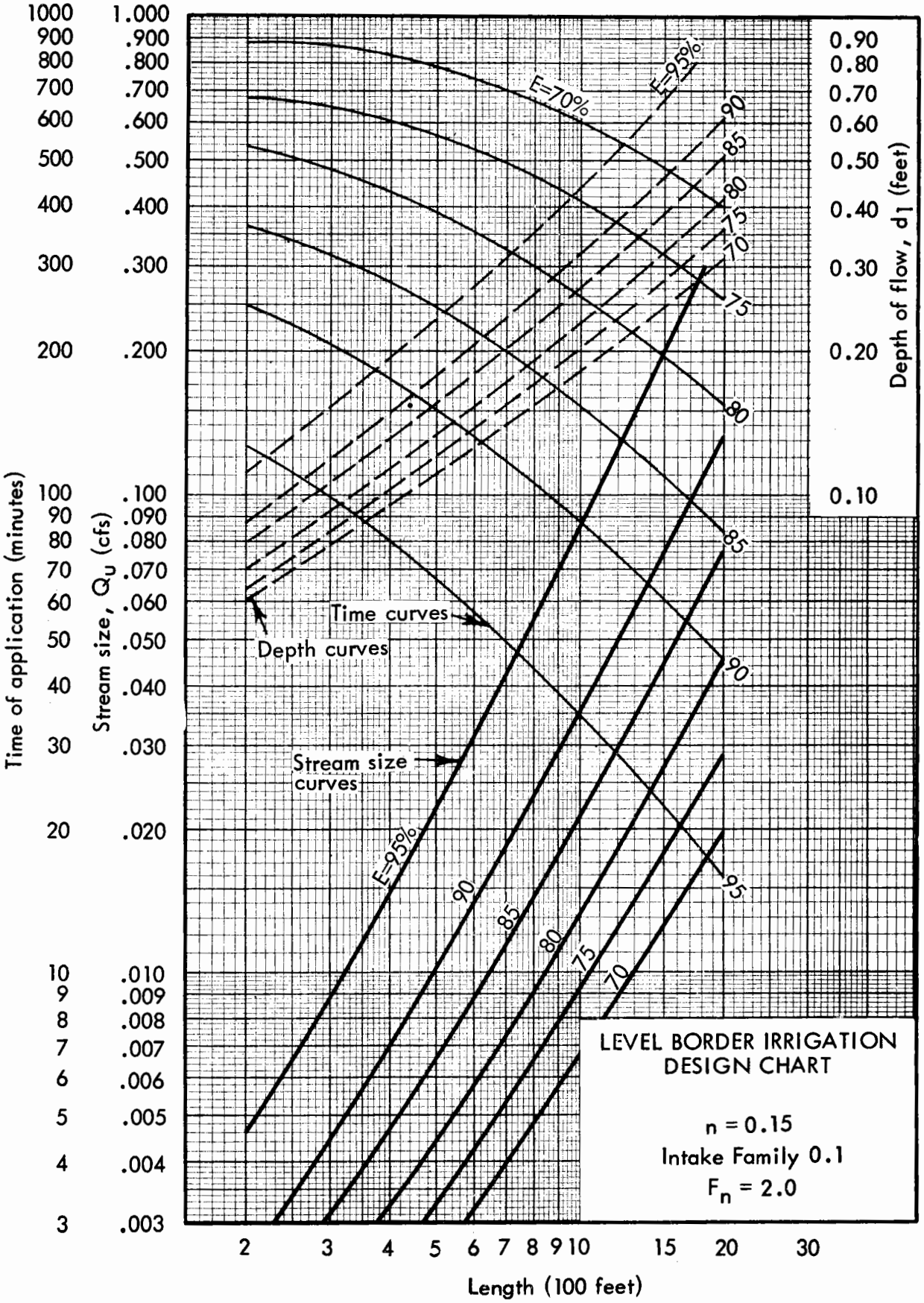

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=75%
70
60
50
E=50%
75
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 2.0

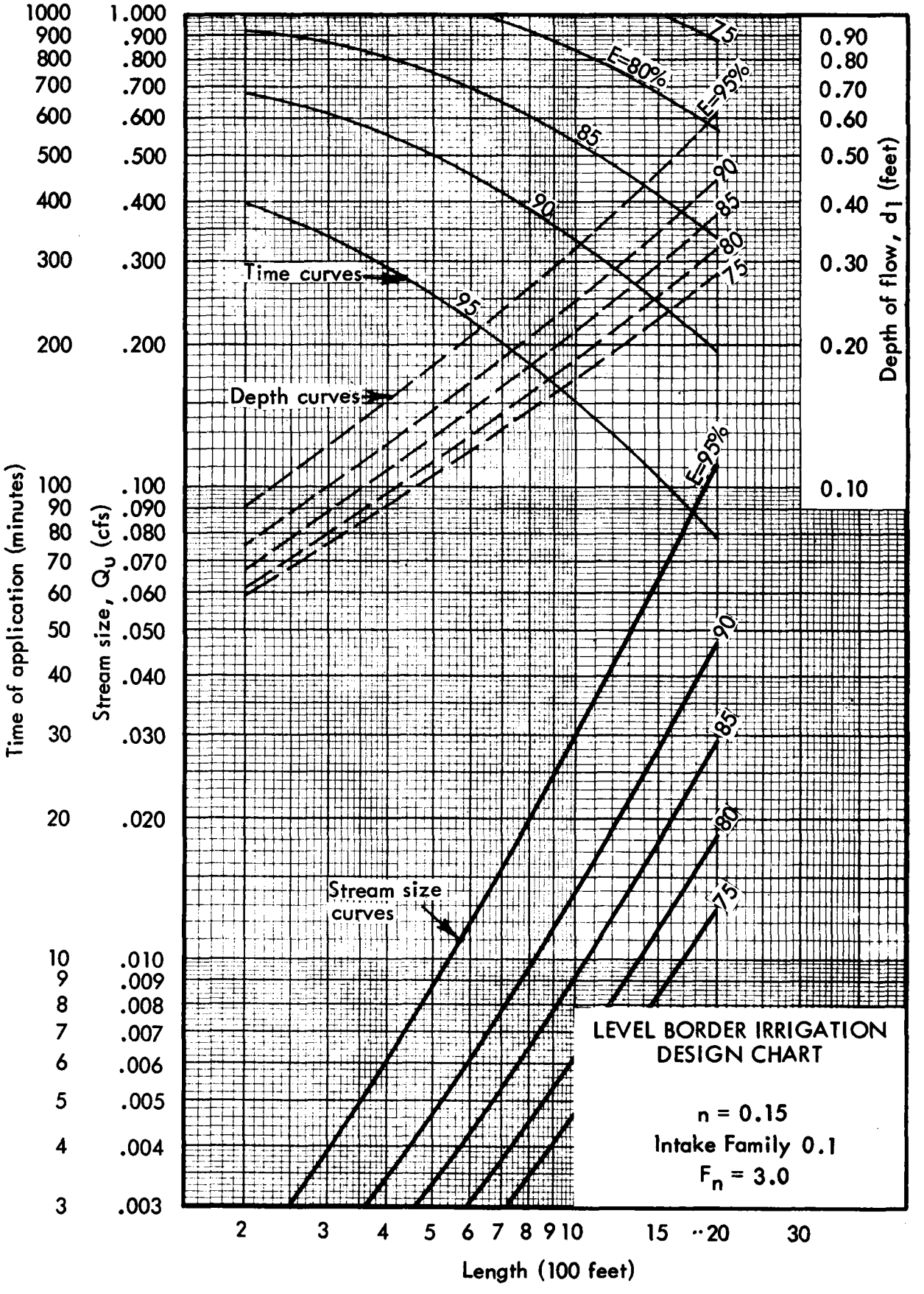

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
E=50%
85
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 3.0

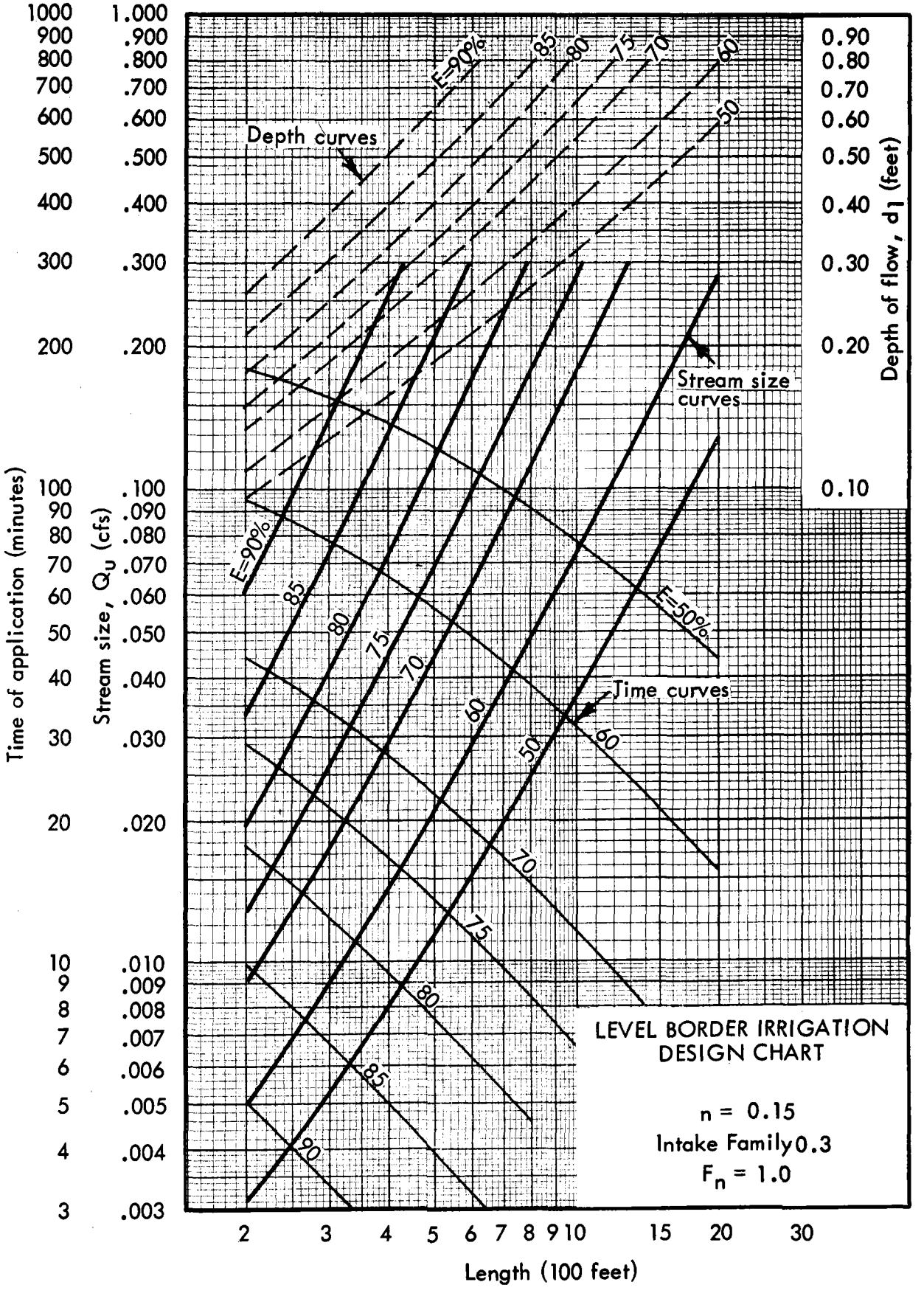

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=20%
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 4.0

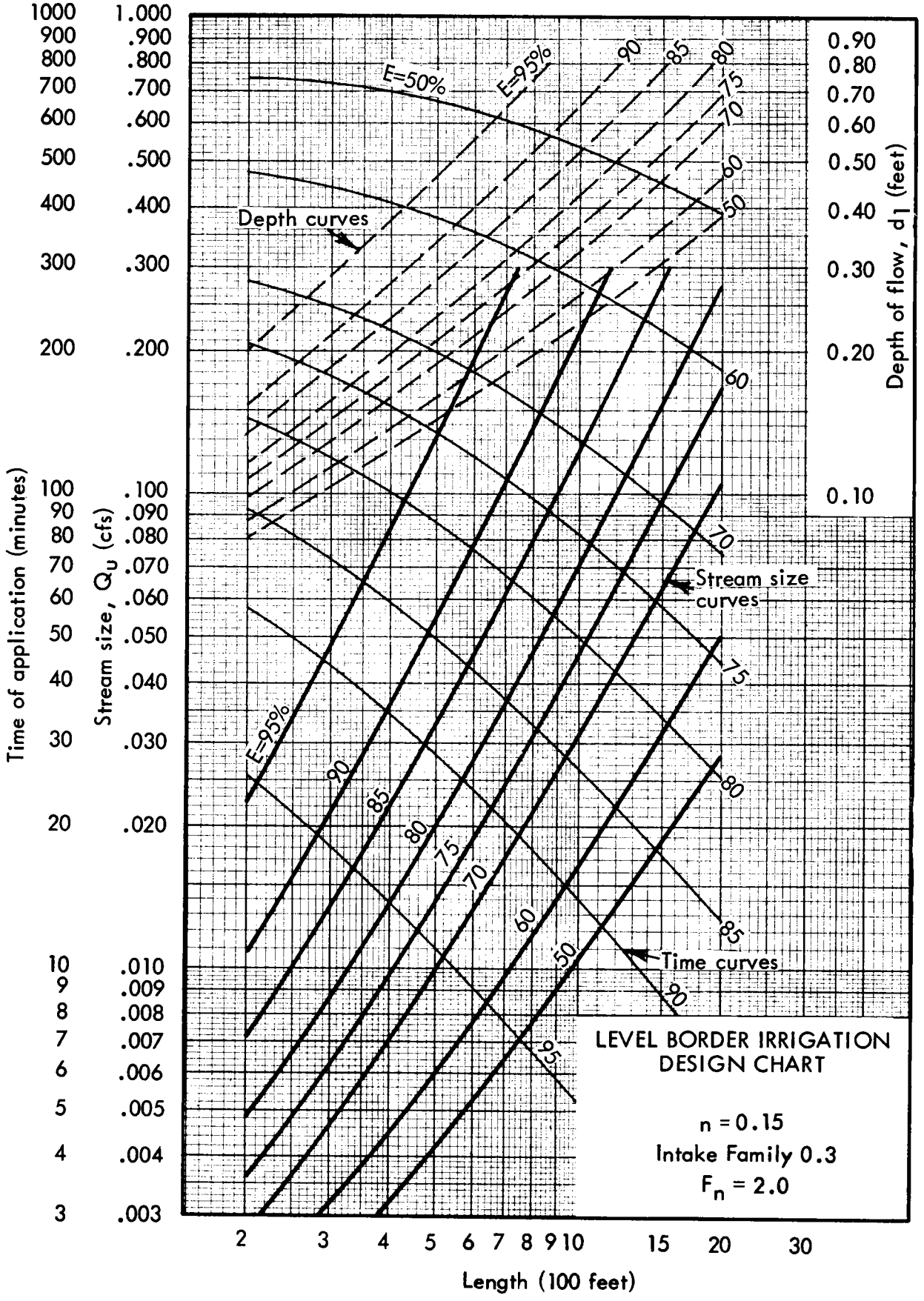

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
85
80
75
70
60
50
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n =5.0

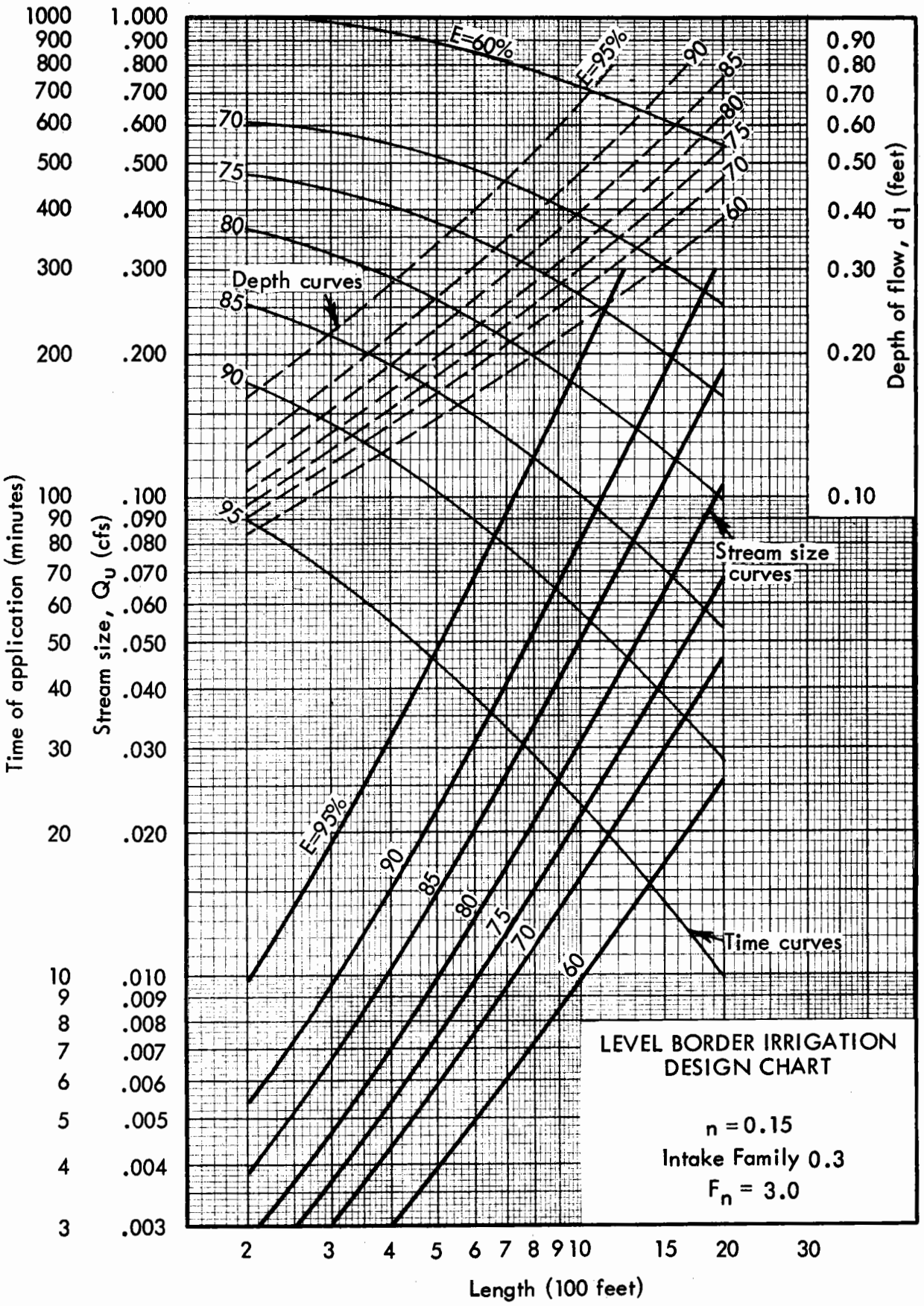

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.1
F_n = 1.0

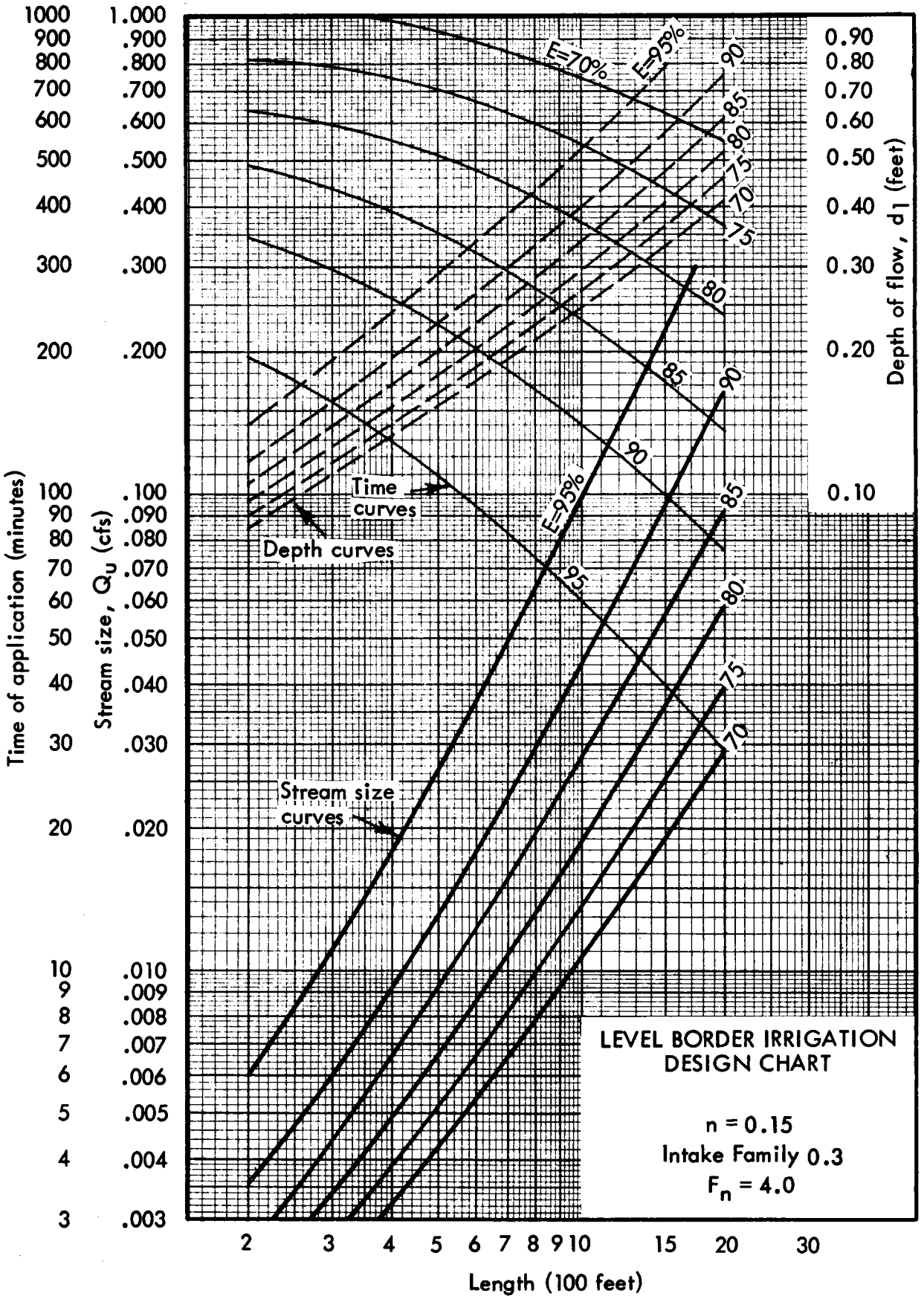

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.1
F_n = 2.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=70%
E=95%
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2
3
4
5
6
7
8
9
10
15
20
30

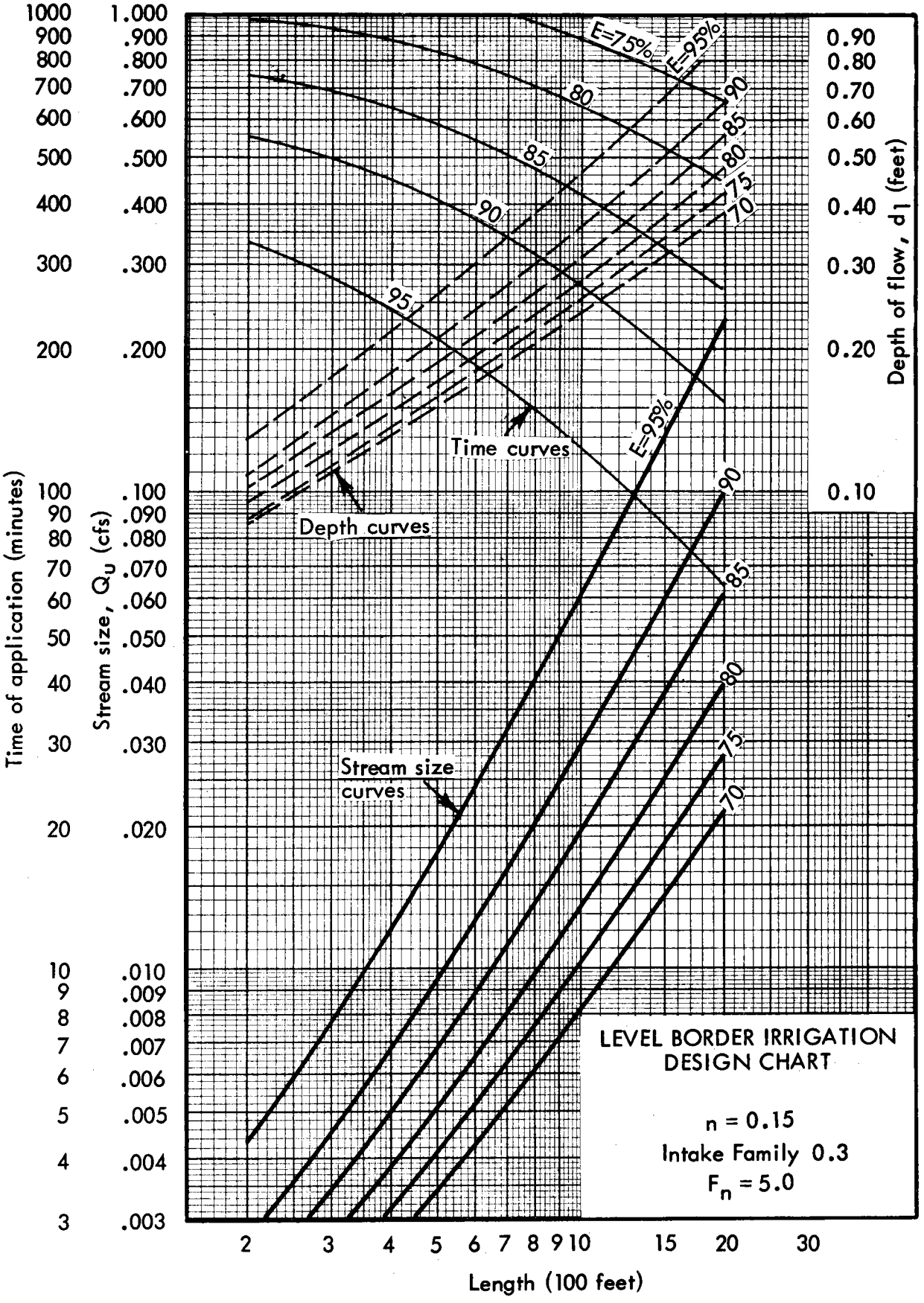

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=80%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.1
F_n = 3.0

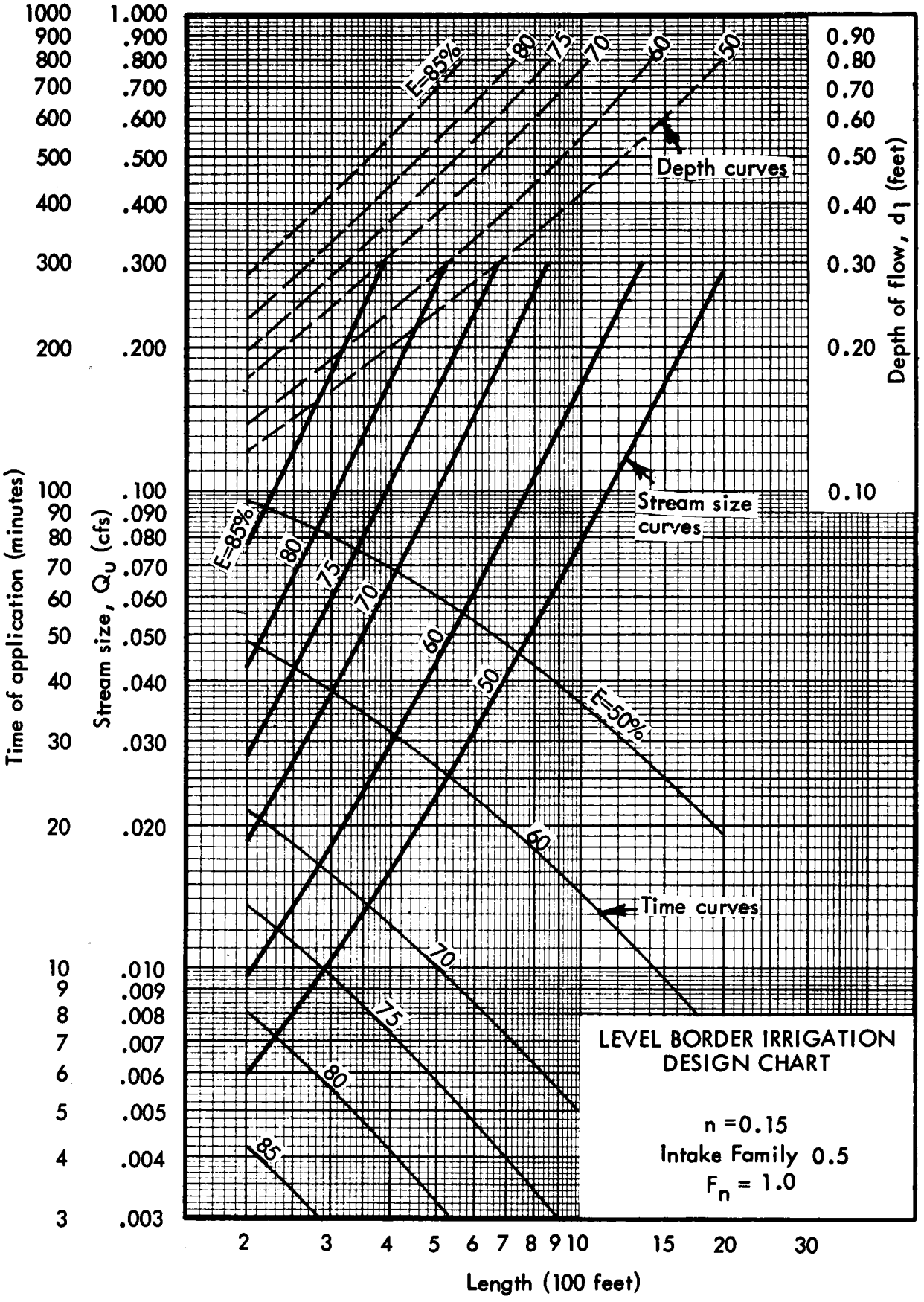

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 1.0

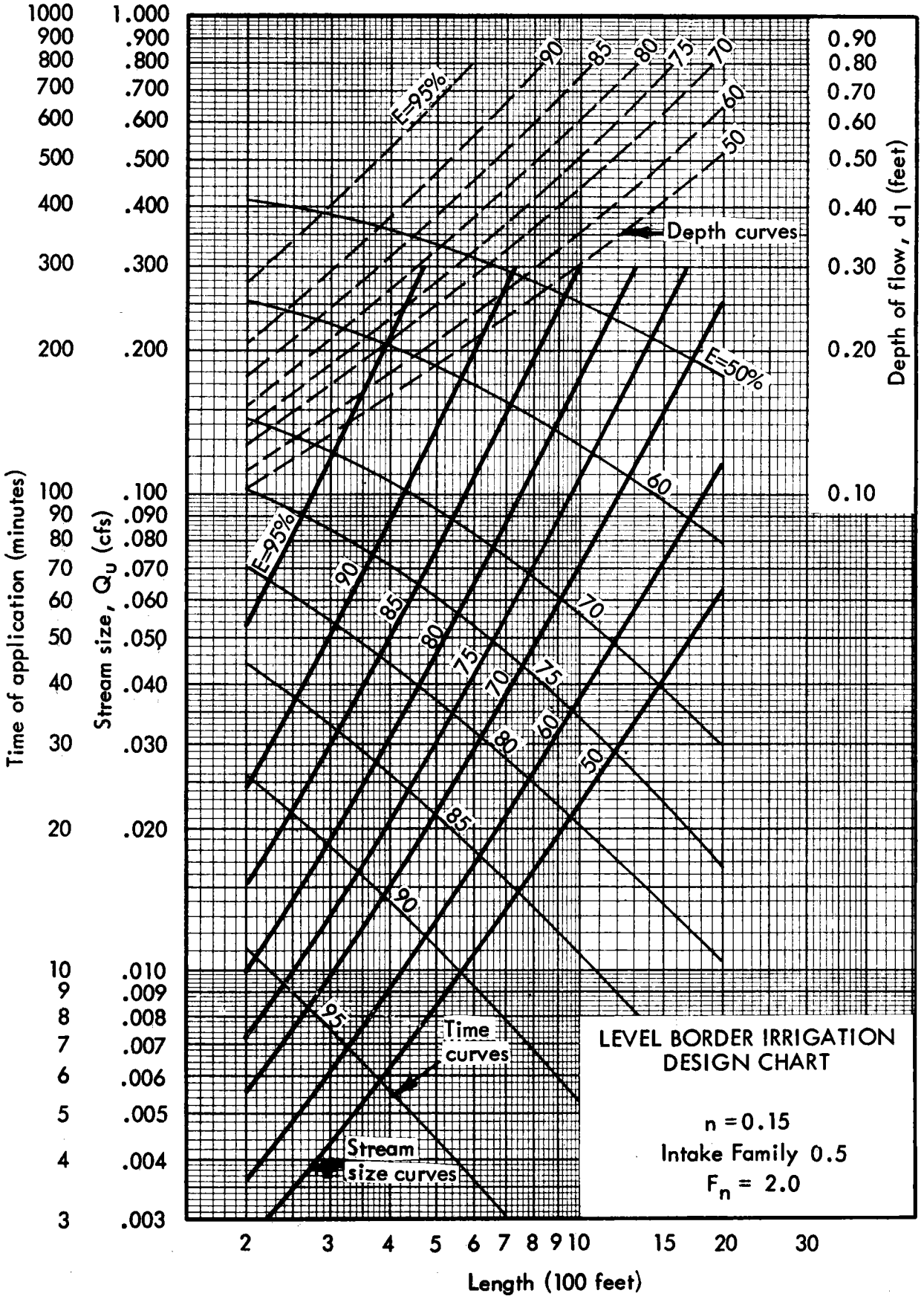

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=50%
E=95%
Depth curves
Stream size curves
Time curves
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 2.0

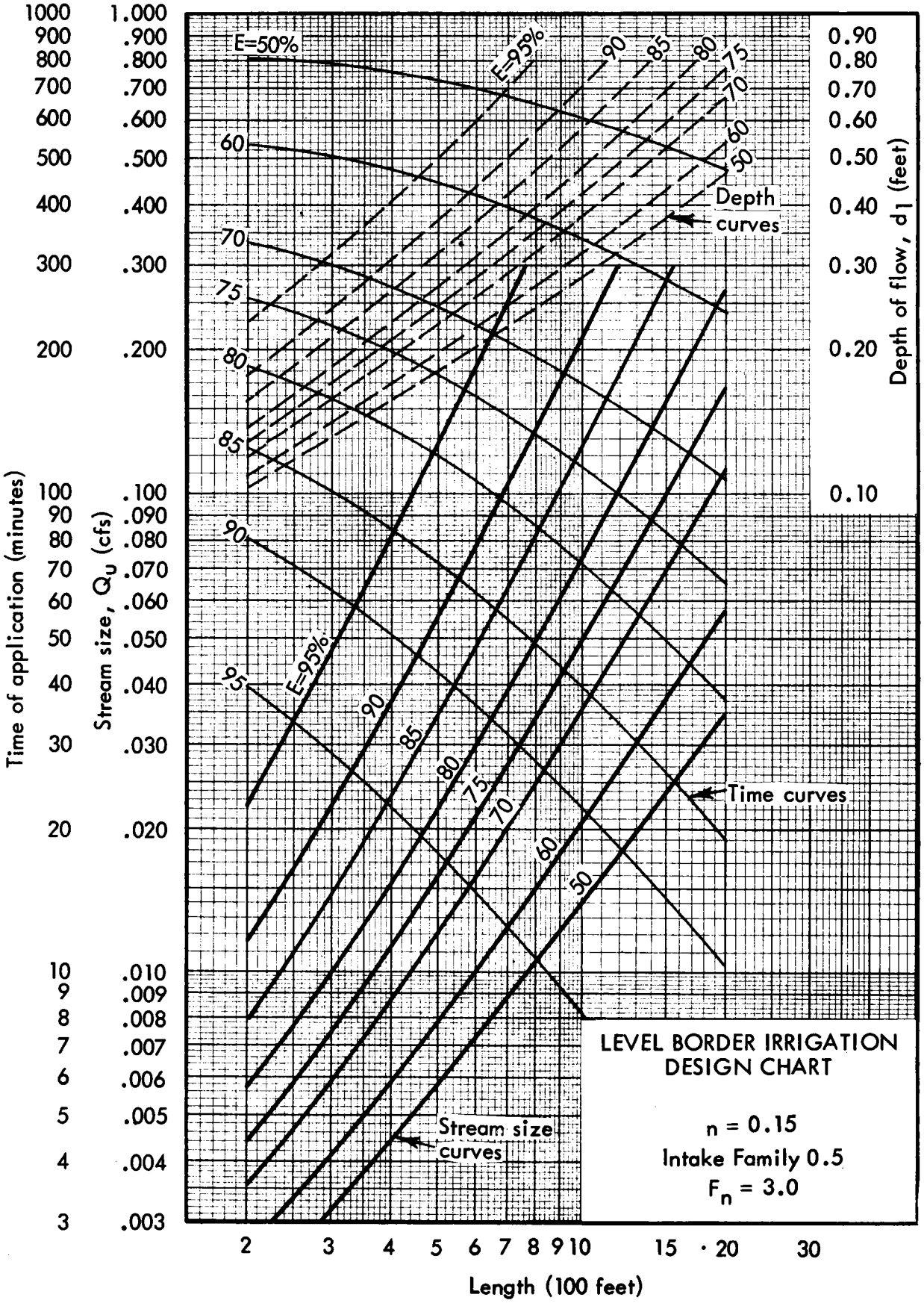

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 3.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=60%
E=95%
E=95%
90
85
80
75
70
60
95

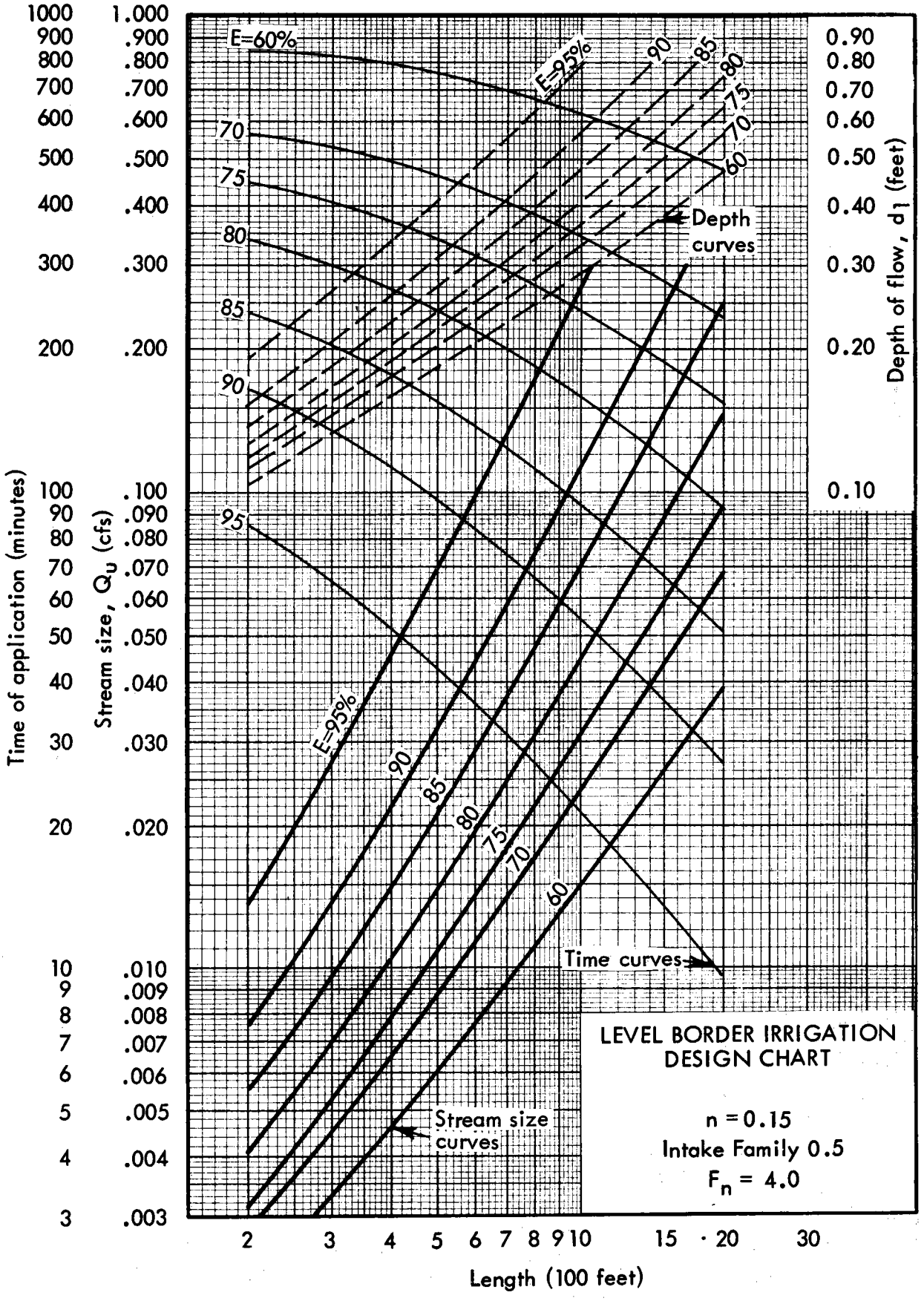

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=70%
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 4.0

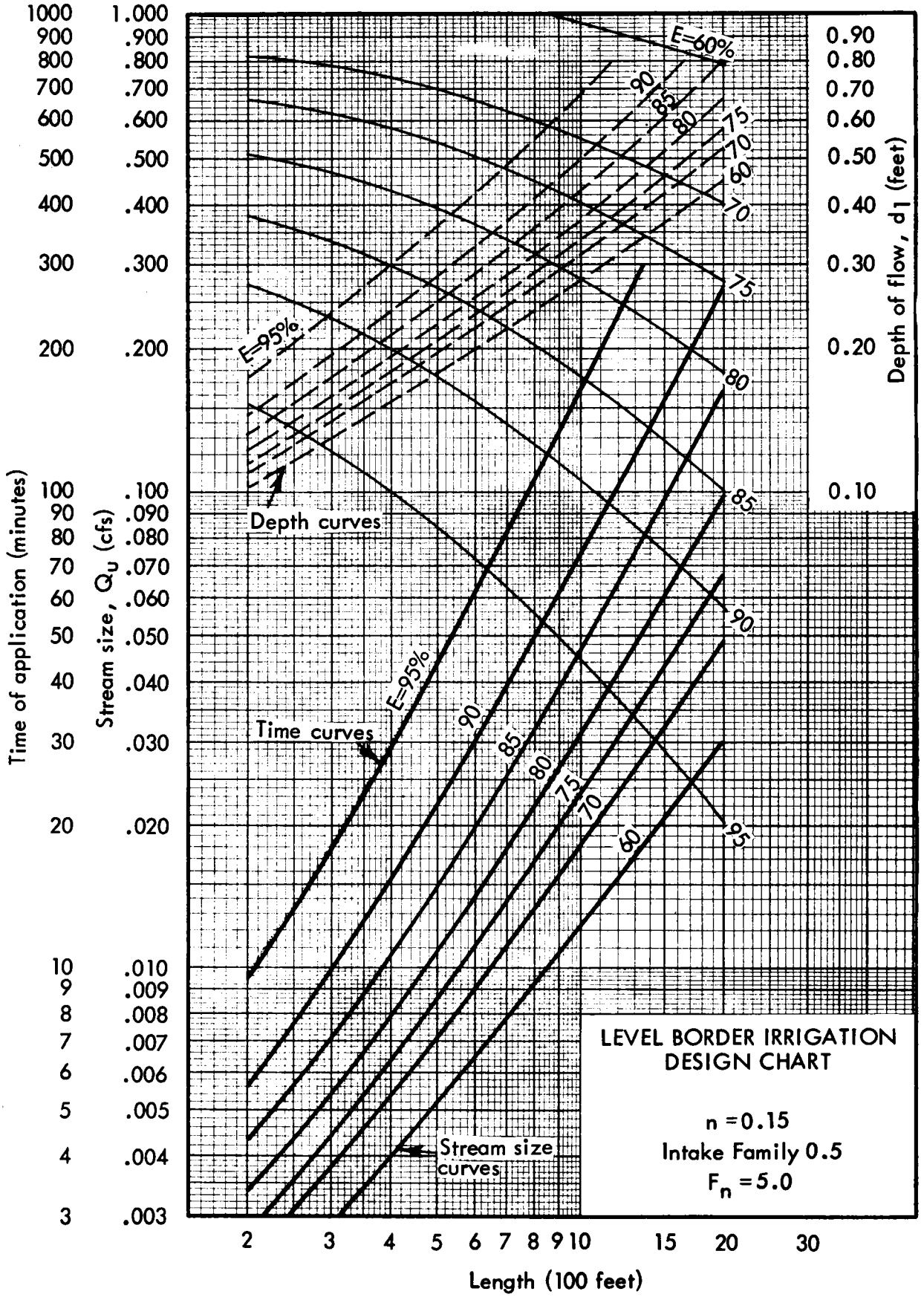

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=75%
E=95%
80
85
90
95
Time curves
Depth curves
Stream size curves
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 5.0

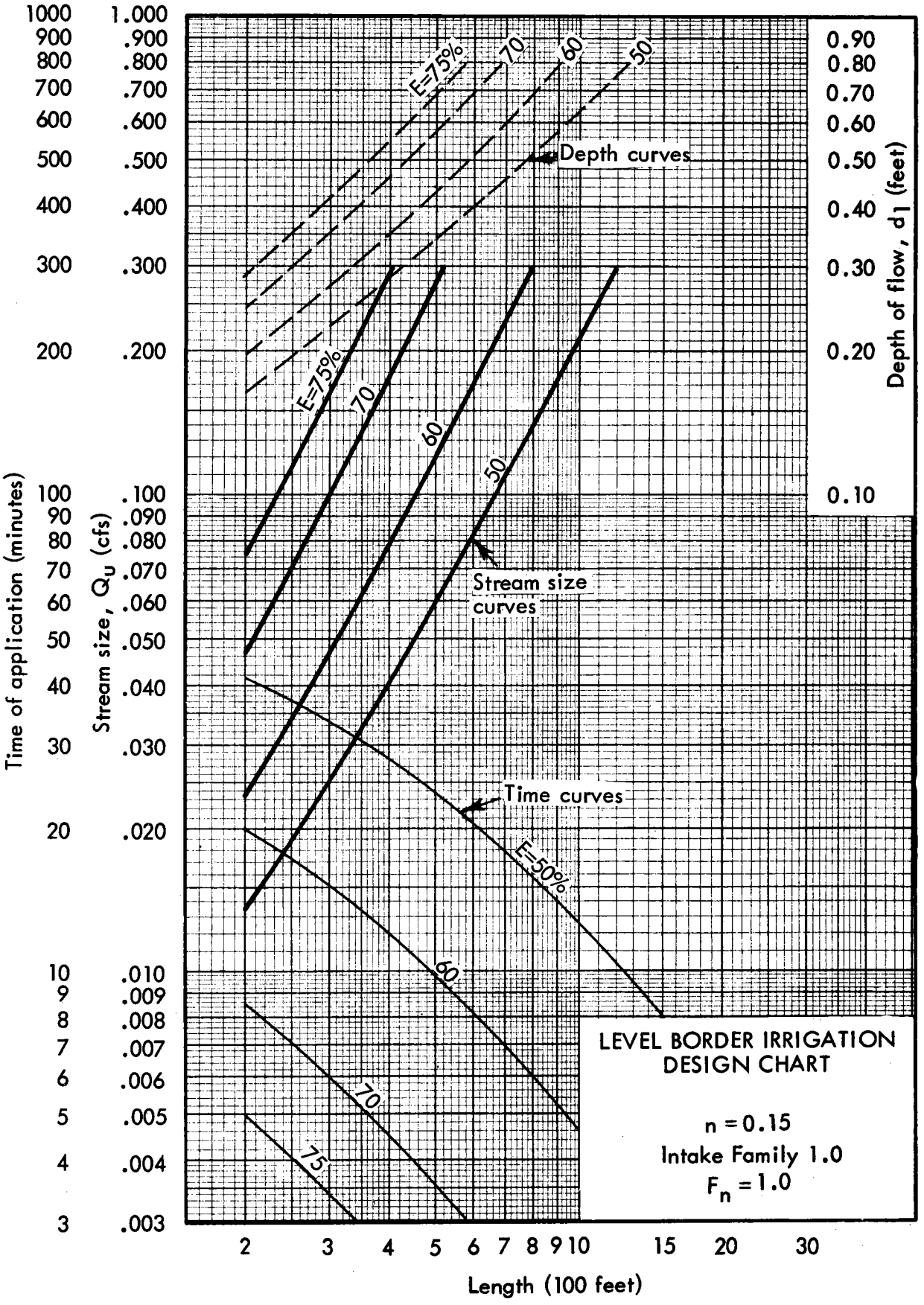

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 1.0
Depth curves
Stream size curves
Time curves
E=85%
E=50%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)

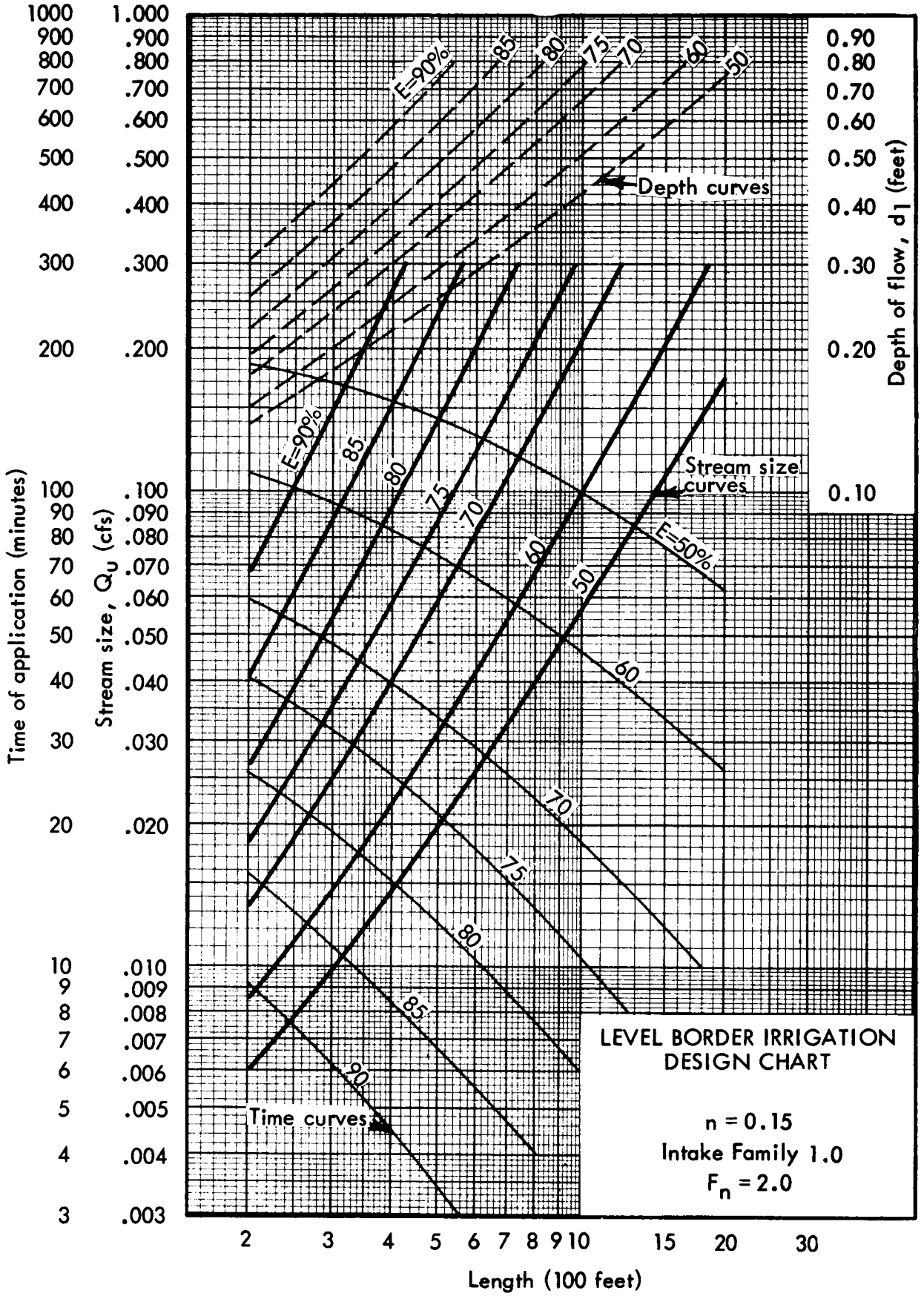

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 2.0
Time curves
Stream size curves
Depth curves
E=95%
E=50%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)

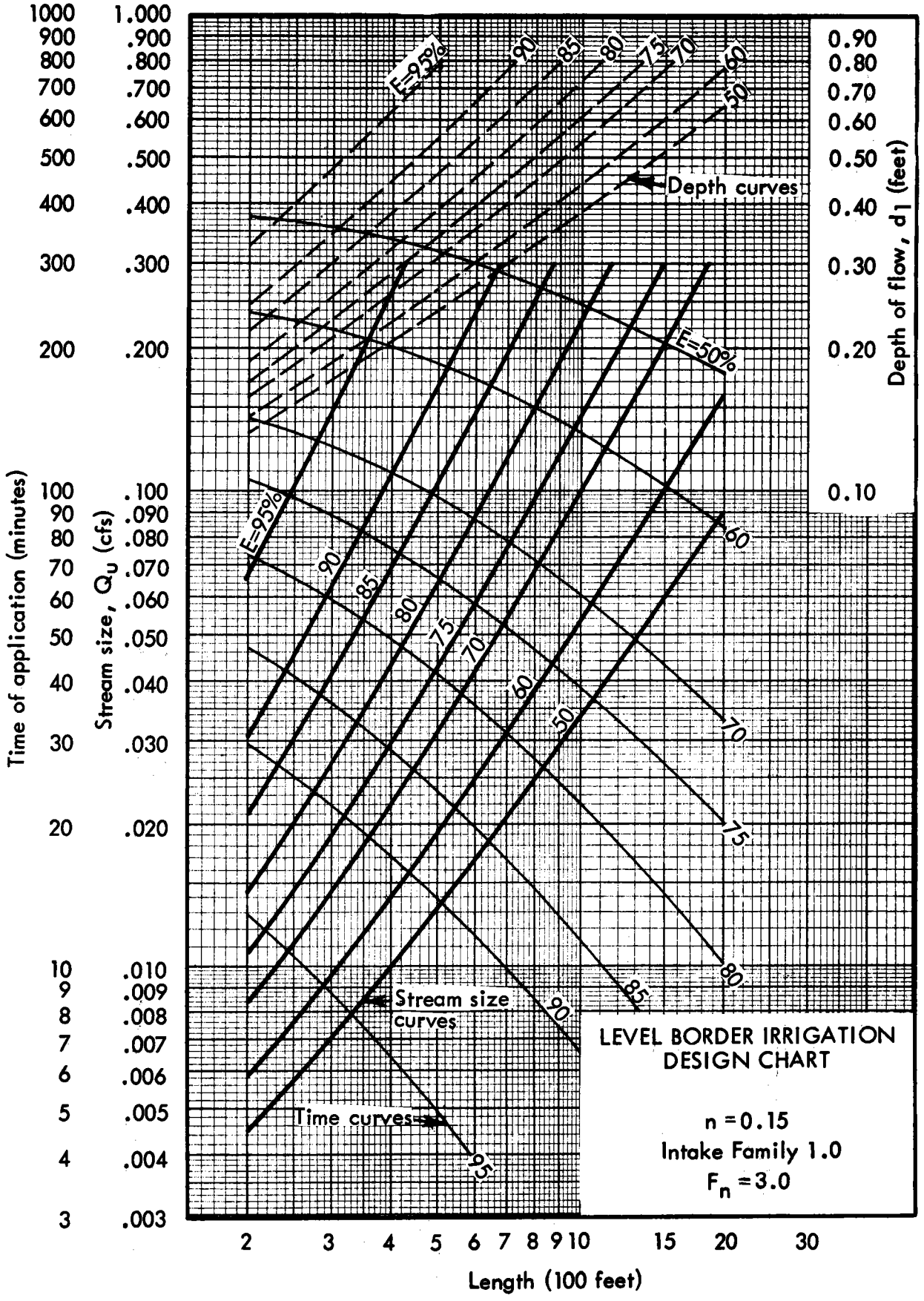

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 3.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Stream size curves
Depth curves
E=50%
E=95%

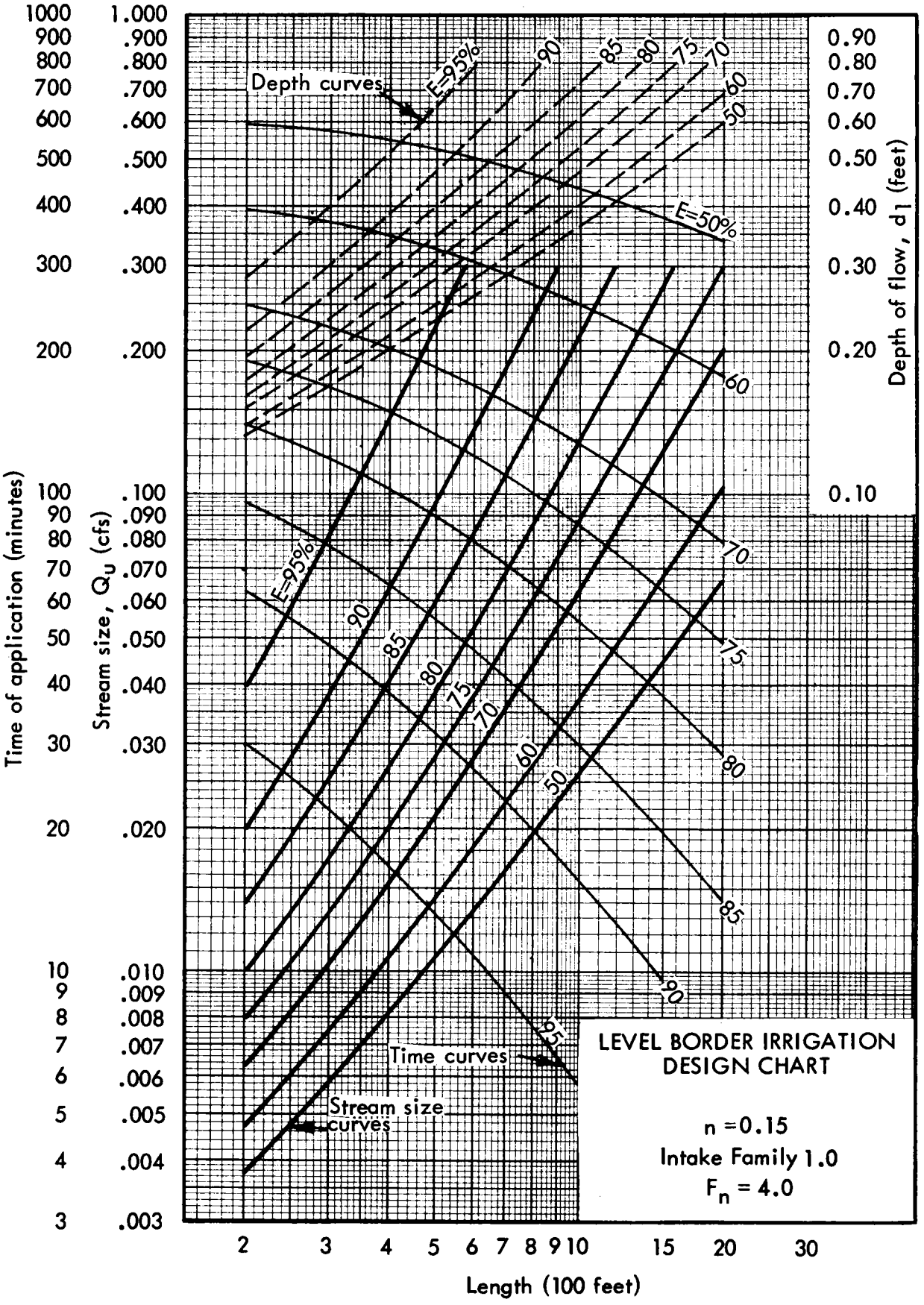

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=60%
E=95%
Depth curves
Time curves
Stream size curves
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 4.0

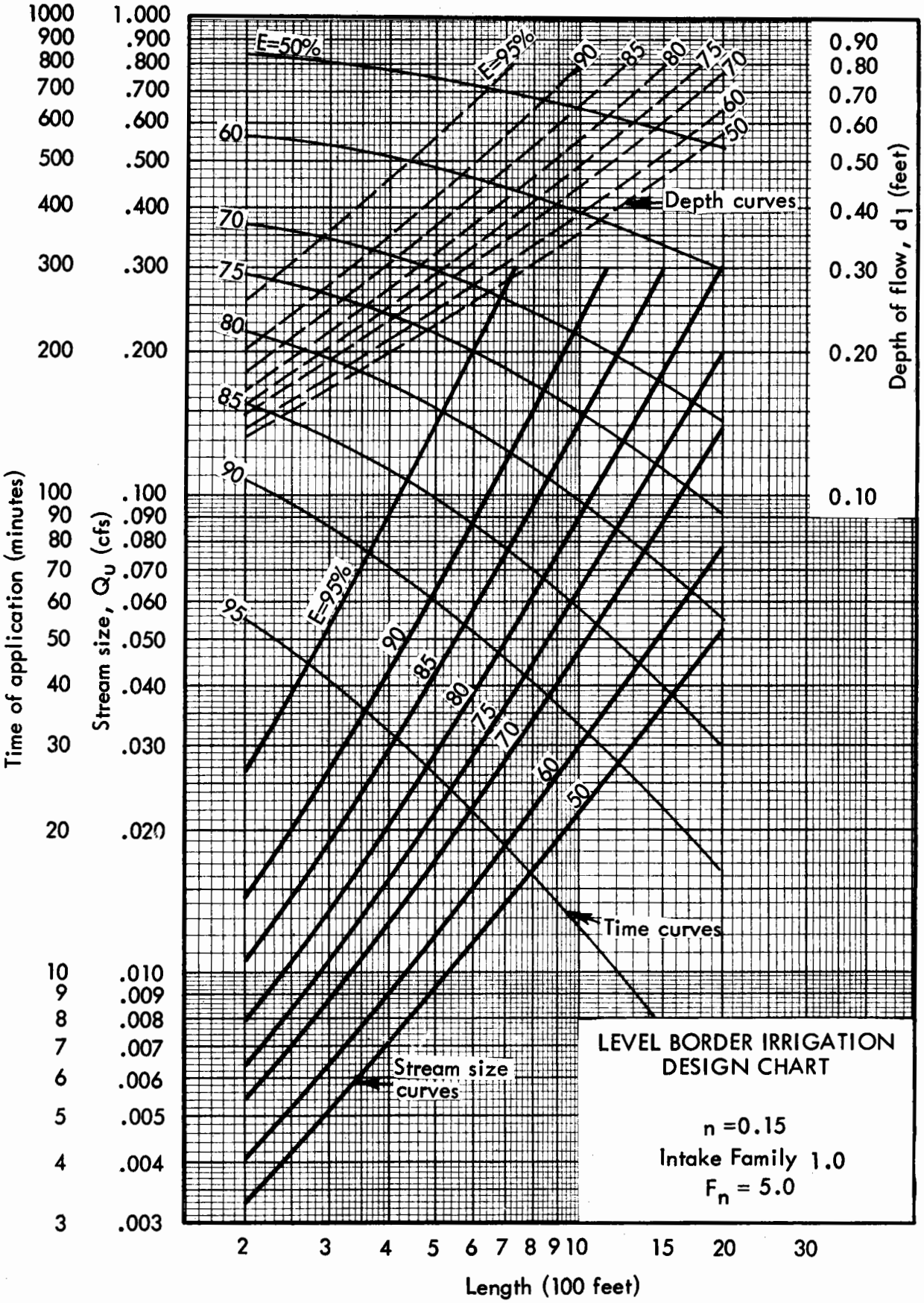

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 5.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=60%
90
85
80
75
70
60
65

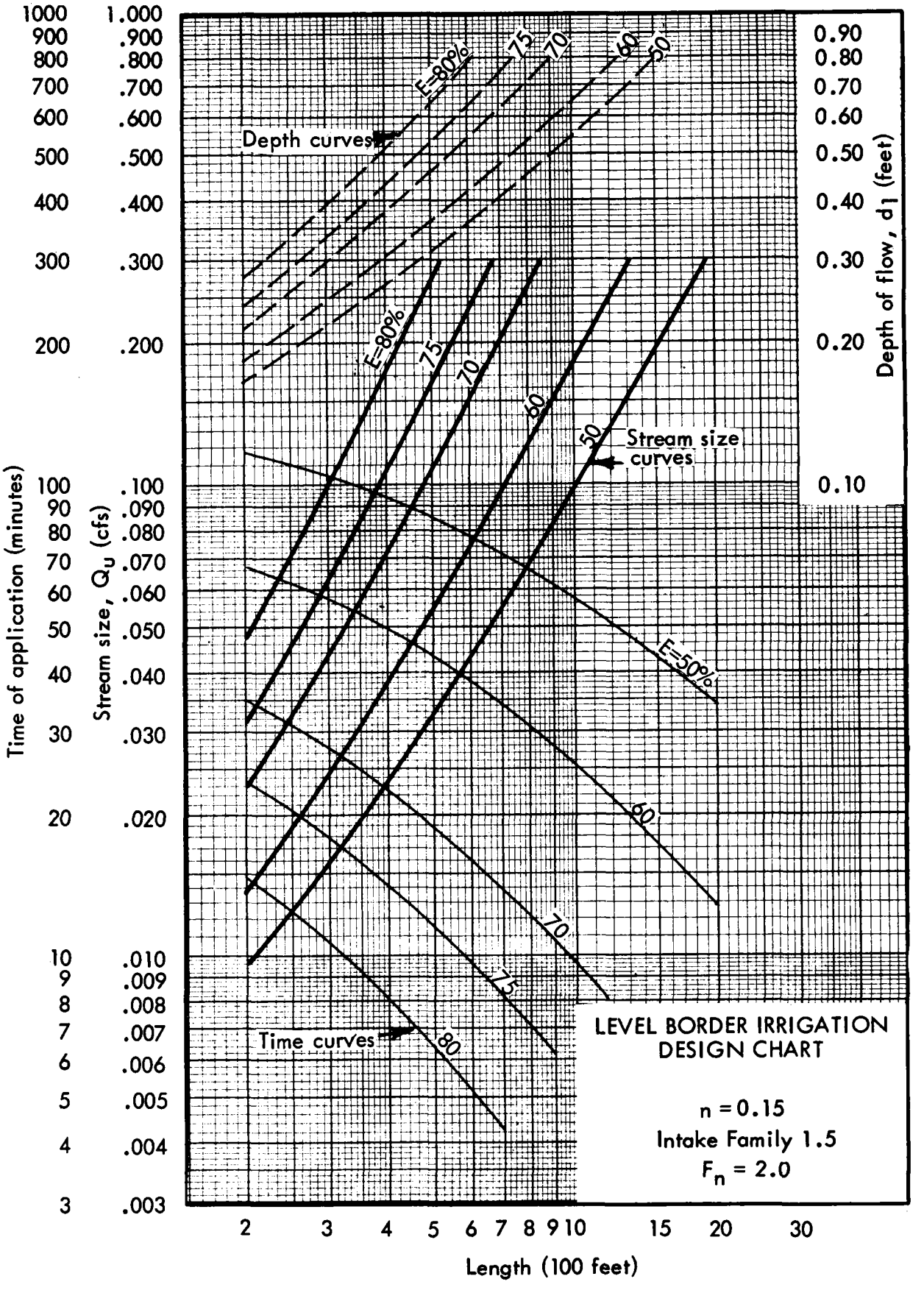

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=75%
70
60
50
E=50%
75
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 1.0

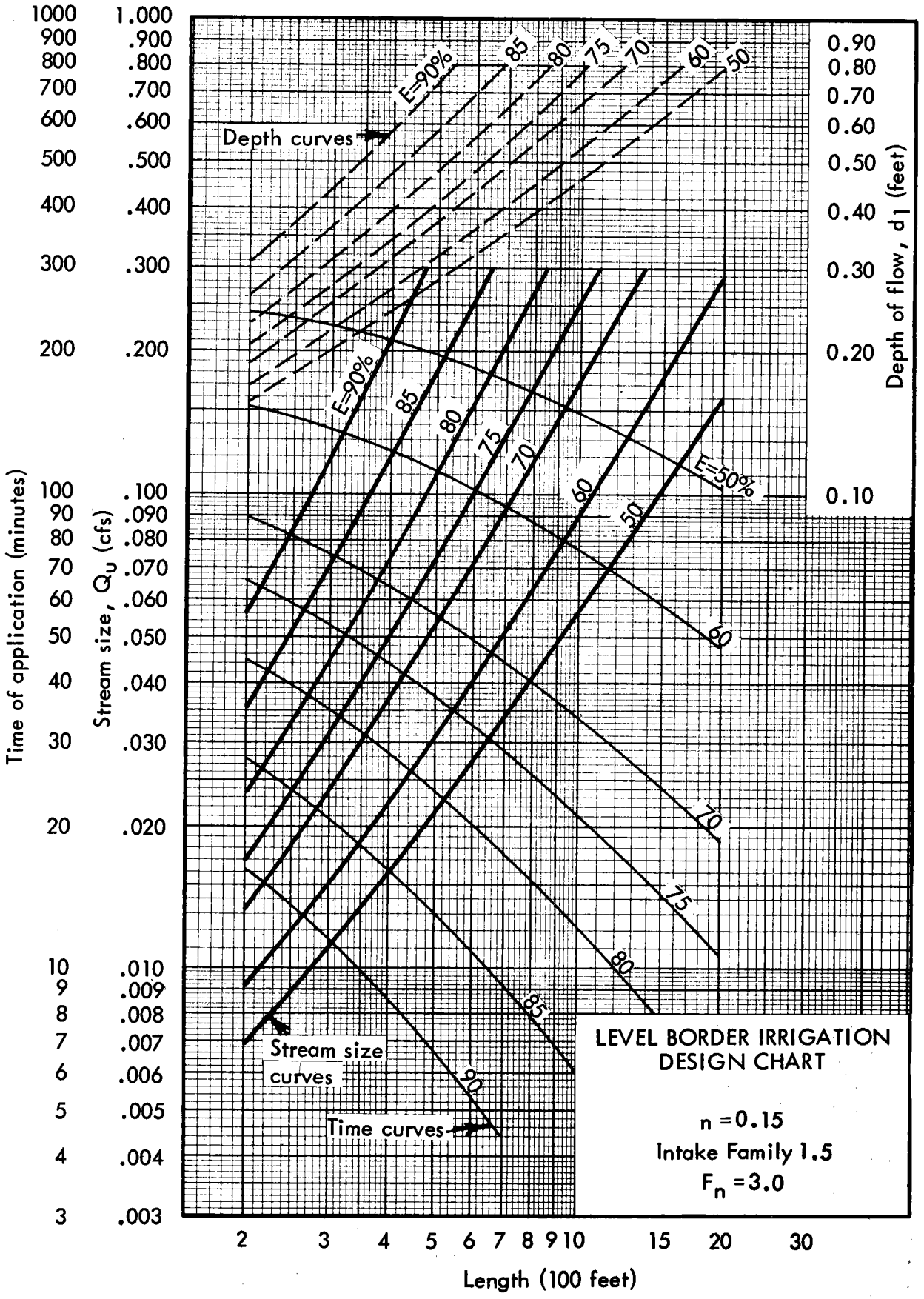

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 2.0
Depth curves
Stream size curves
Time curves
E=90%
85
80
75
70
60
50
E=50%
90
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 900 800 700 600 500 400 300 200 100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3
1.000 .900 .800 .700 .600 .500 .400 .300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003
0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10
2 3 4 5 6 7 8 9 10 15 20 30

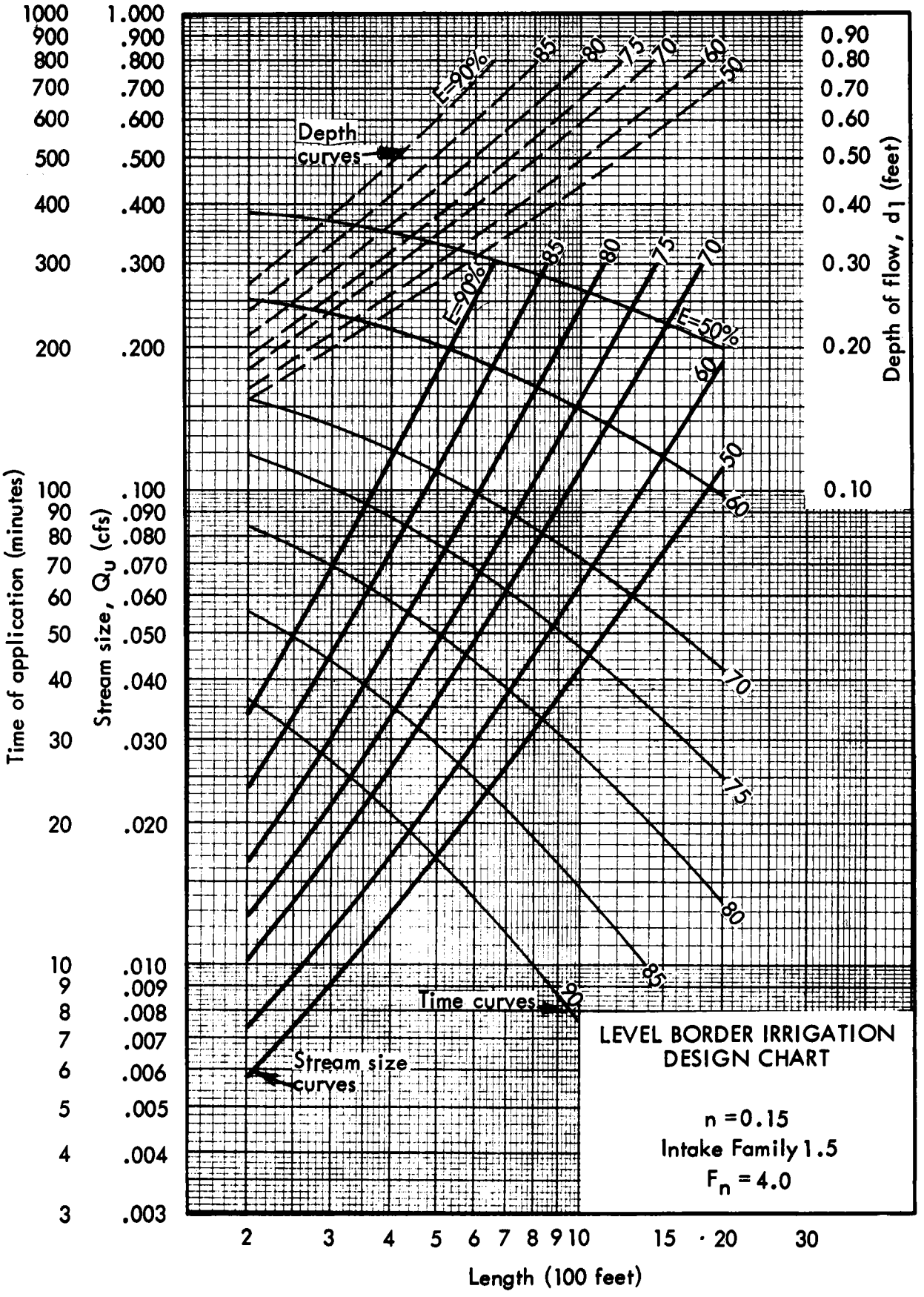

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 3.0

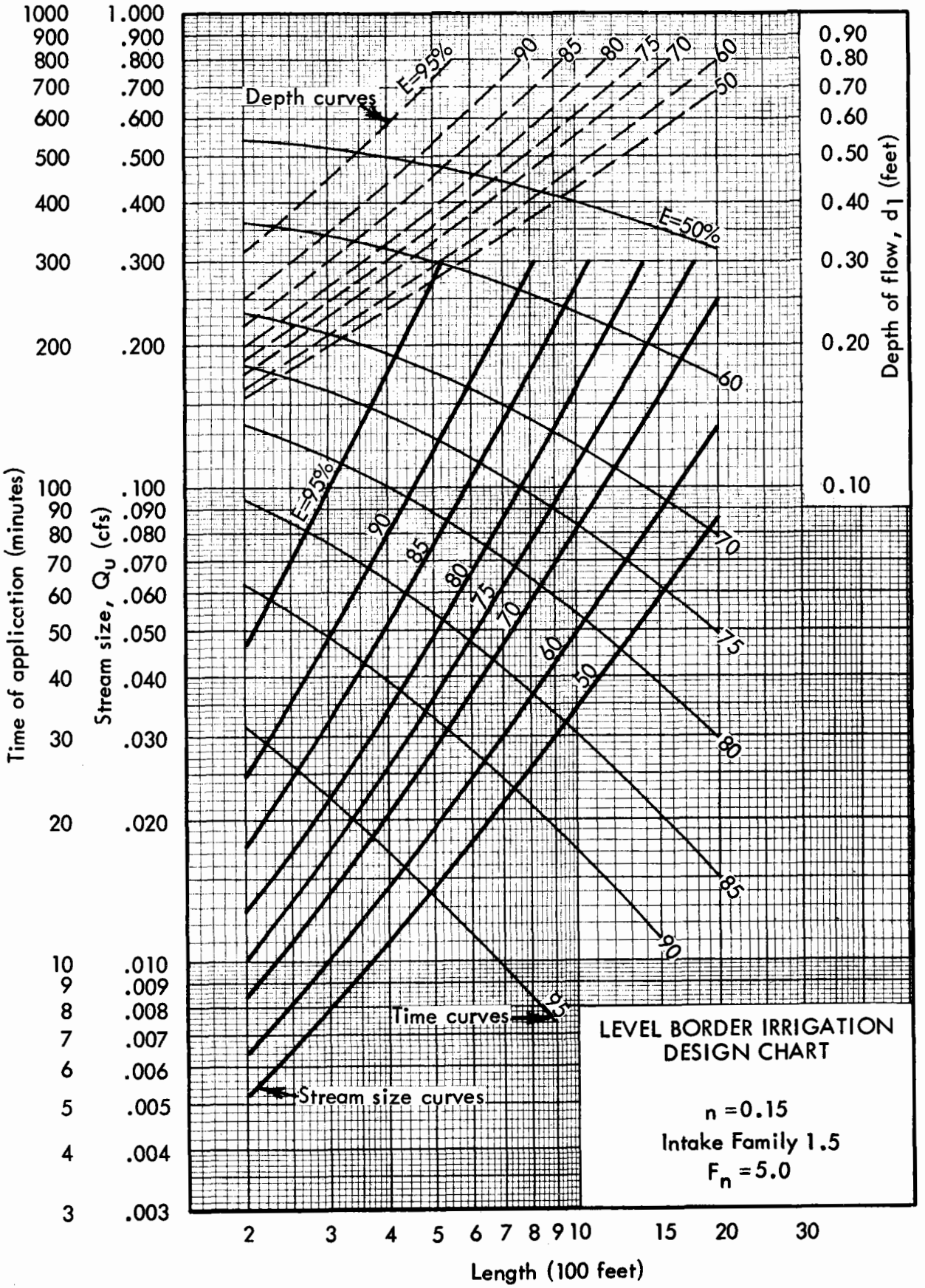

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 4.0

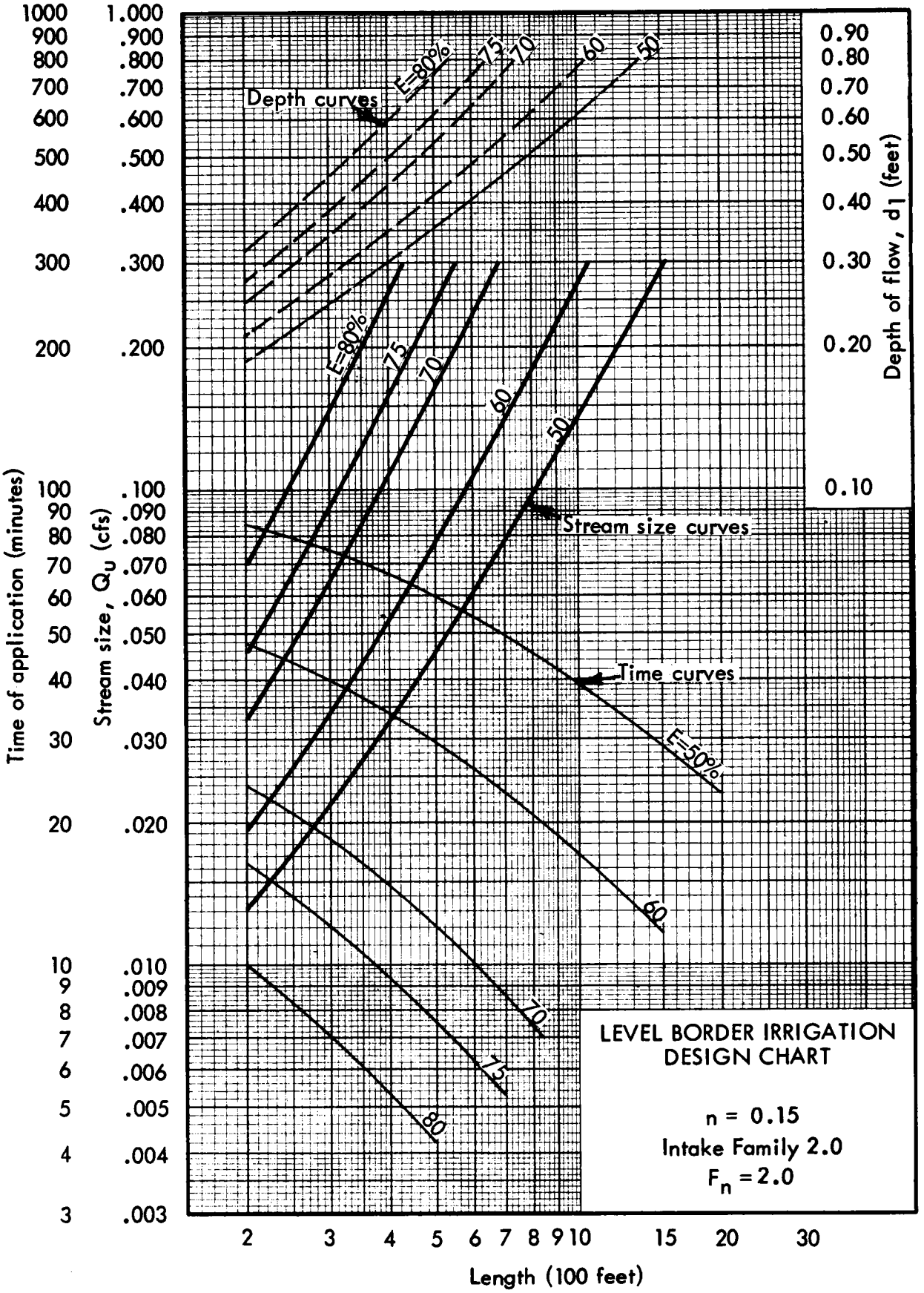

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 5.0
Time of application (minutes)
Stream size, Q_U (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=50%
E=95%
Depth curves
Time curves
Stream size curves

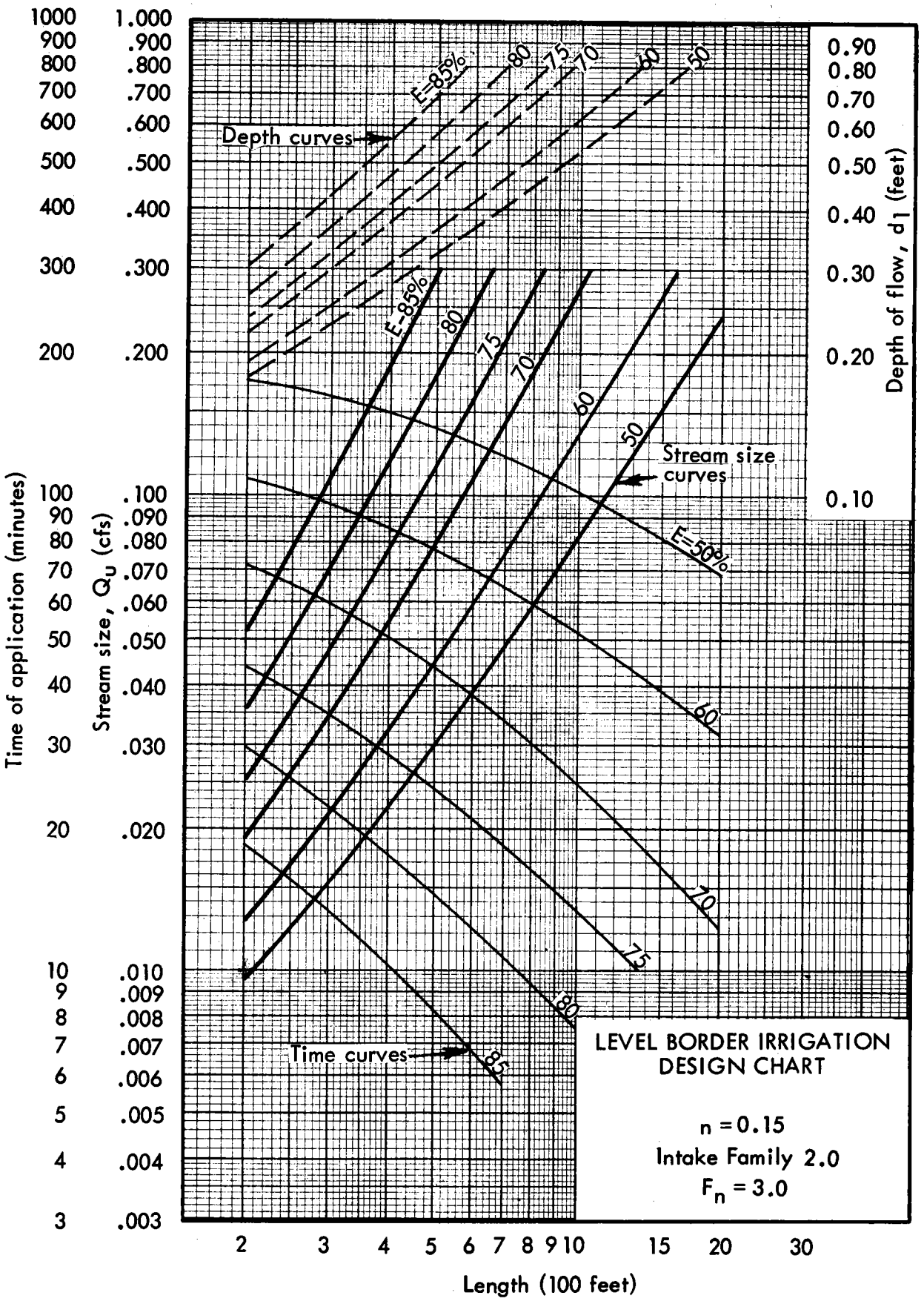

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
80
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 2.0

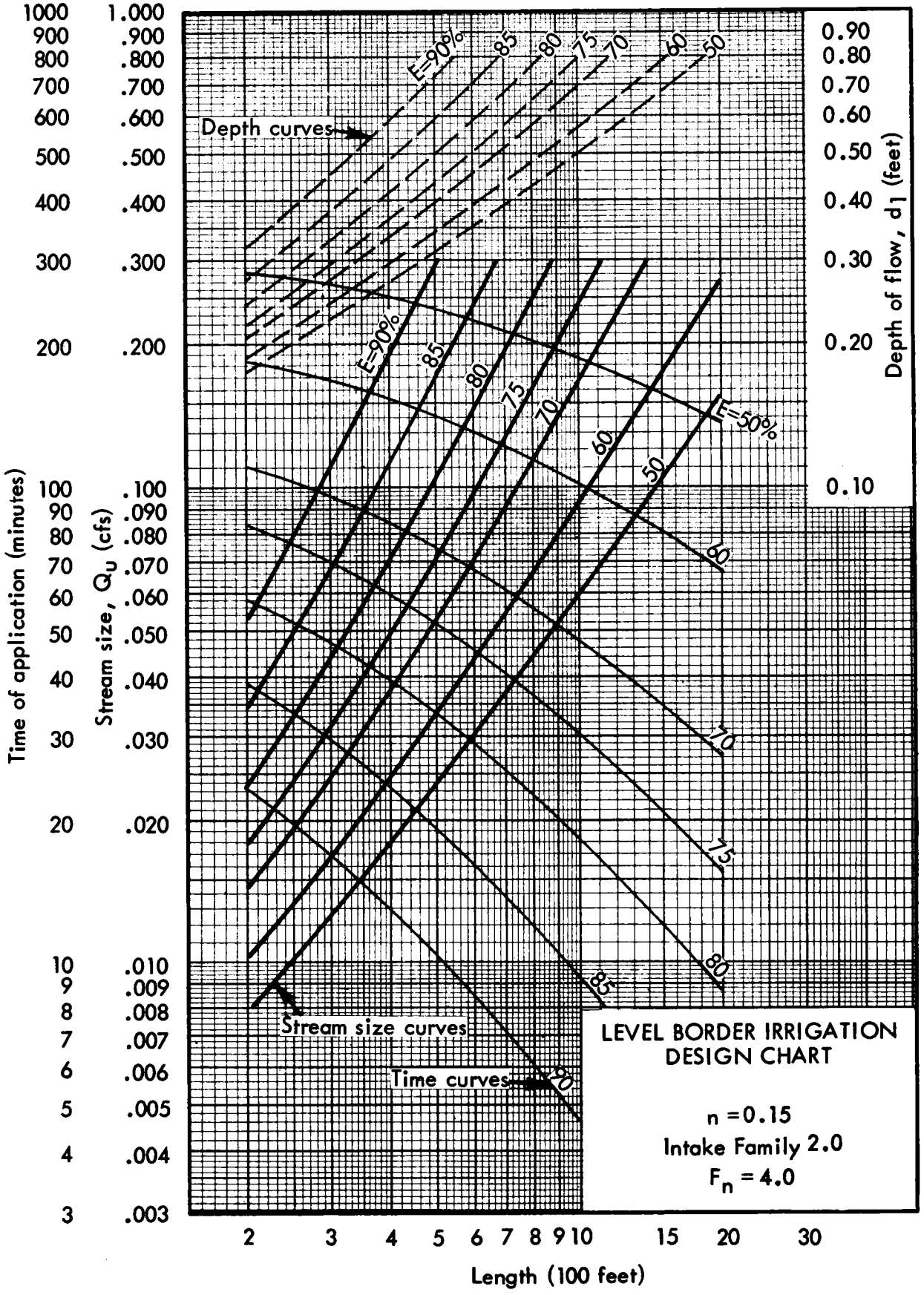

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
85
80
75
70
60
50
ET=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 3.0

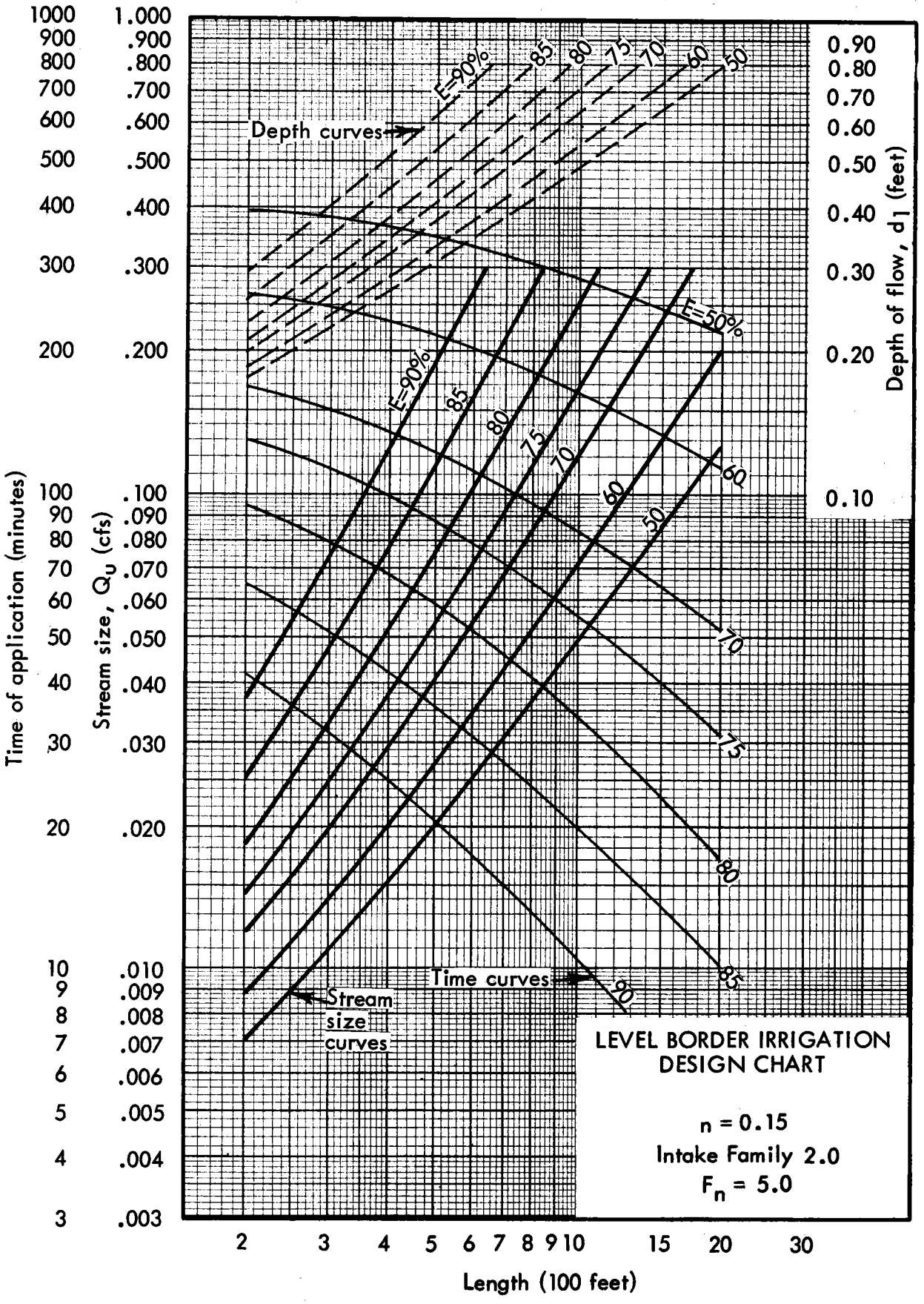

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 4.0

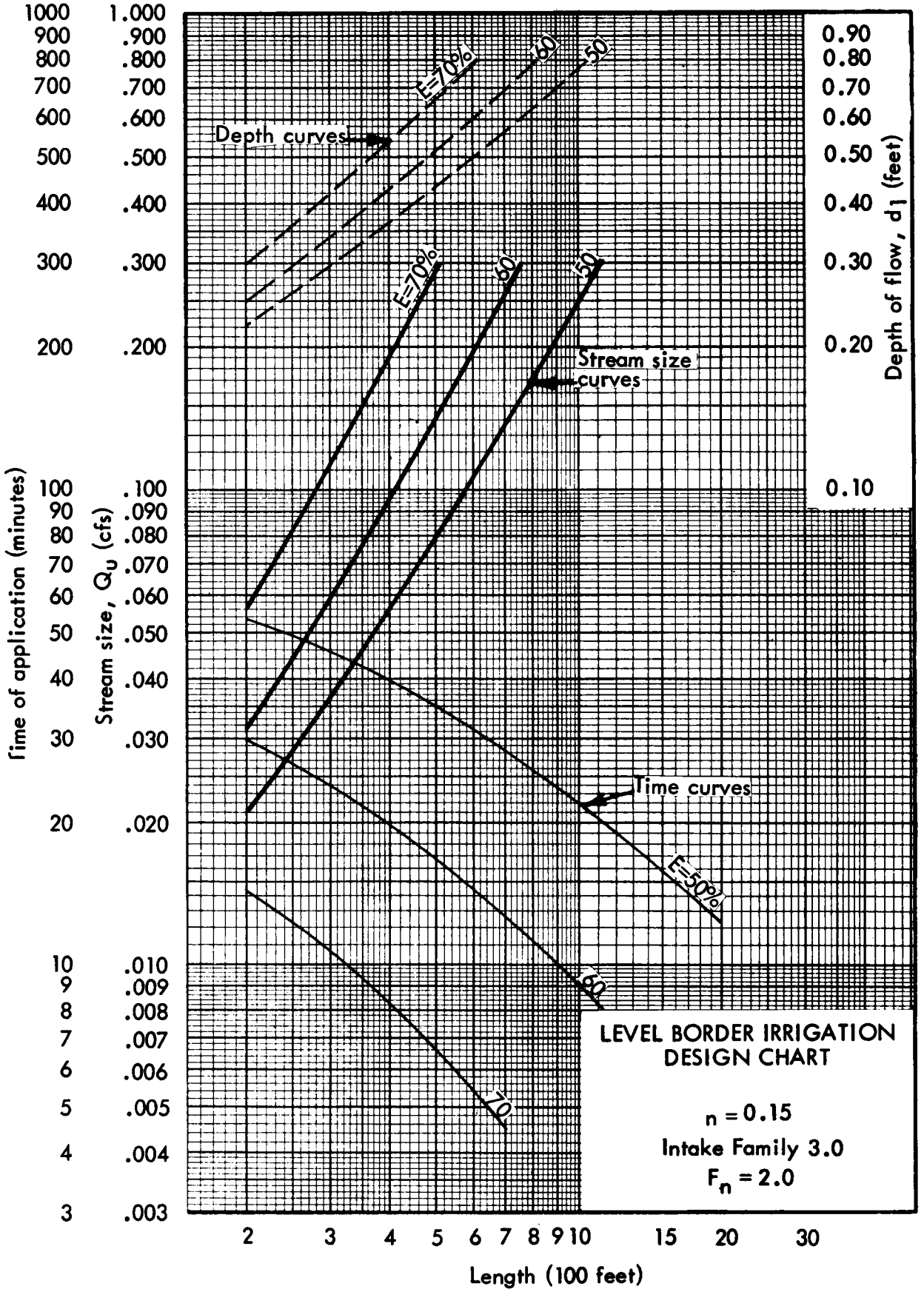

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 5.0

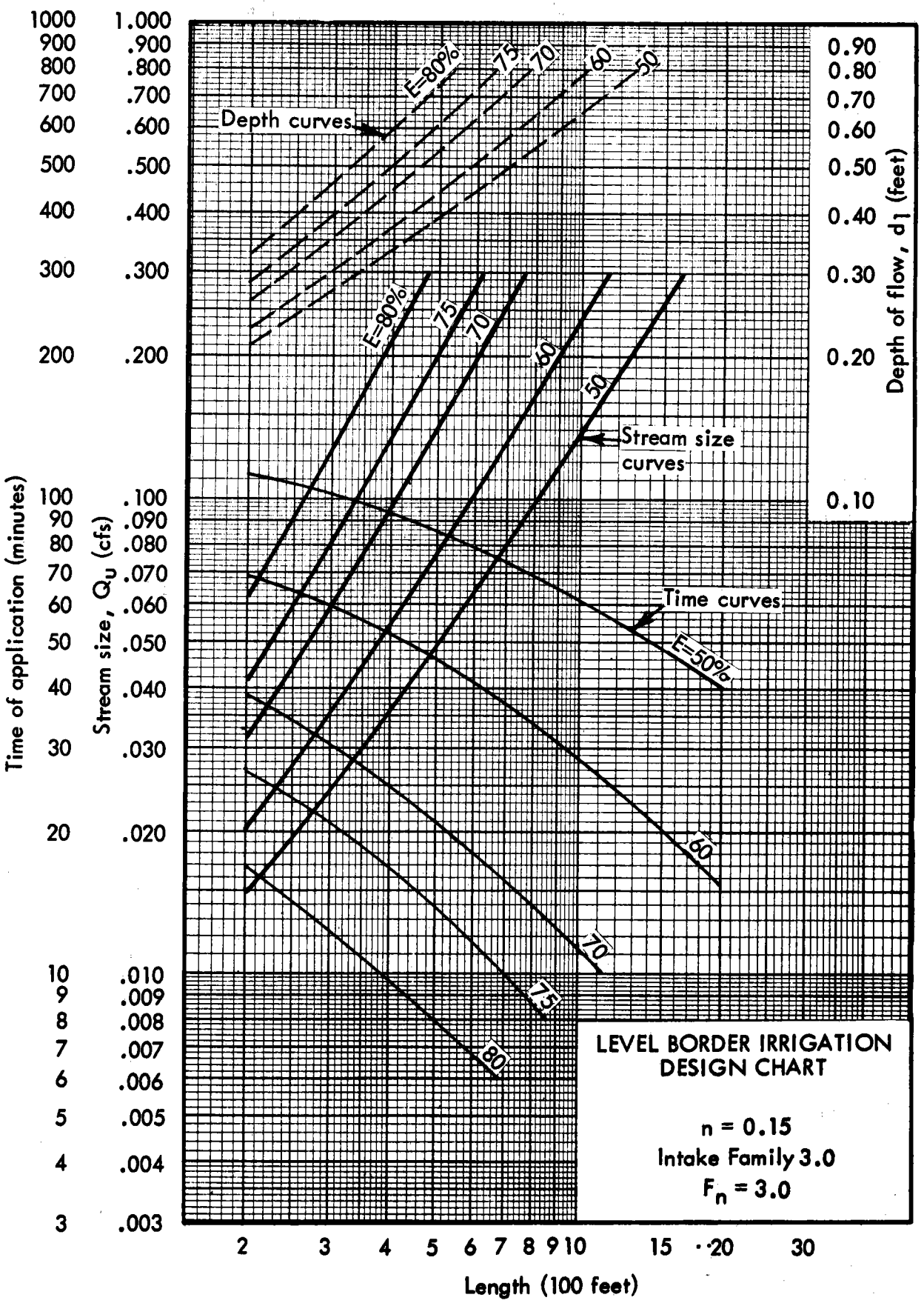

Depth curves
E=80%
75
70
60
50
Stream size curves
Time curves
E=50%
60
70
75
80
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 2.0

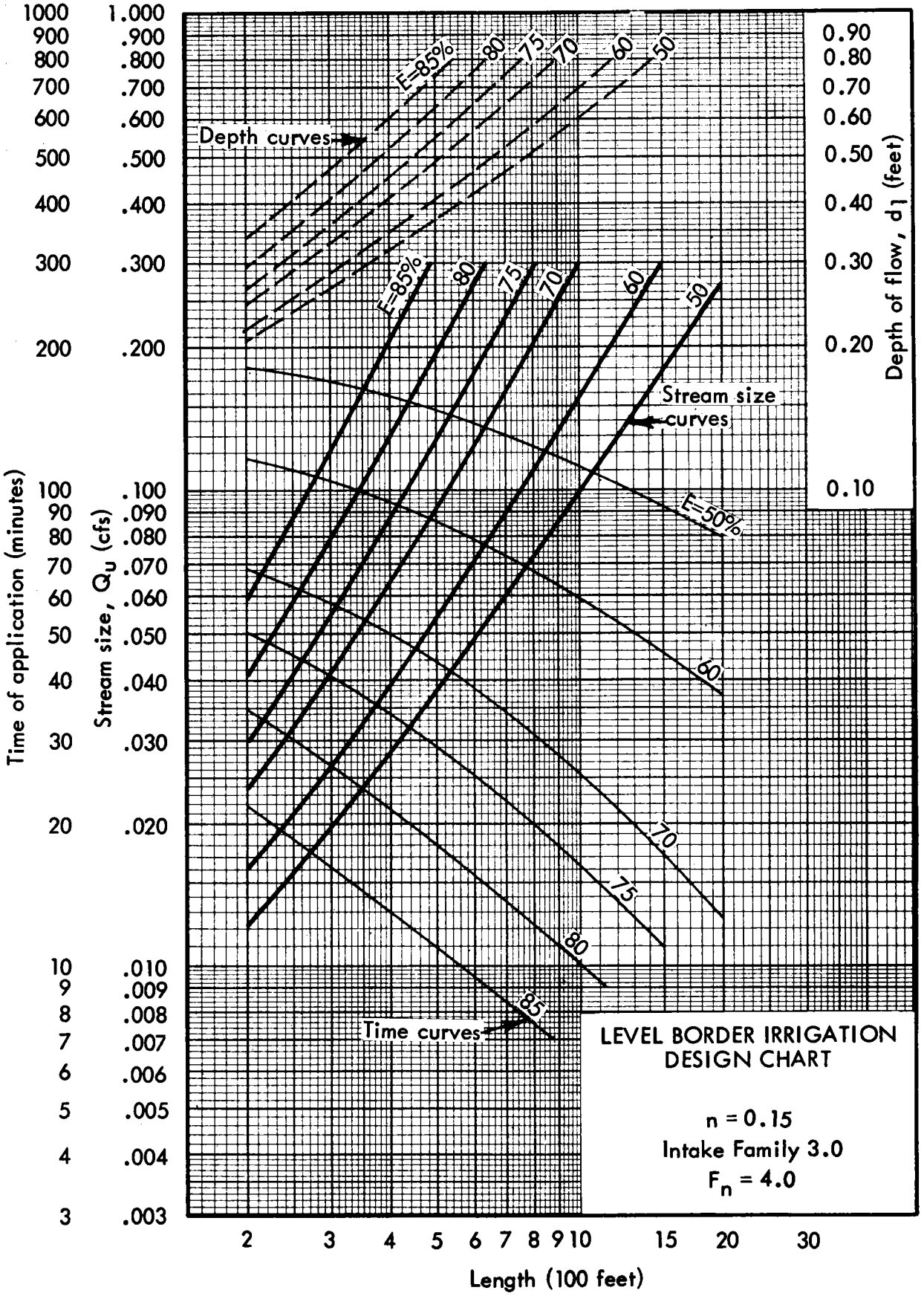

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 3.0
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
E=50%
85
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 900 800 700 600 500 400 300 200 100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3
1.000 .900 .800 .700 .600 .500 .400 .300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003
0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10
2 3 4 5 6 7 8 9 10 15 20 30

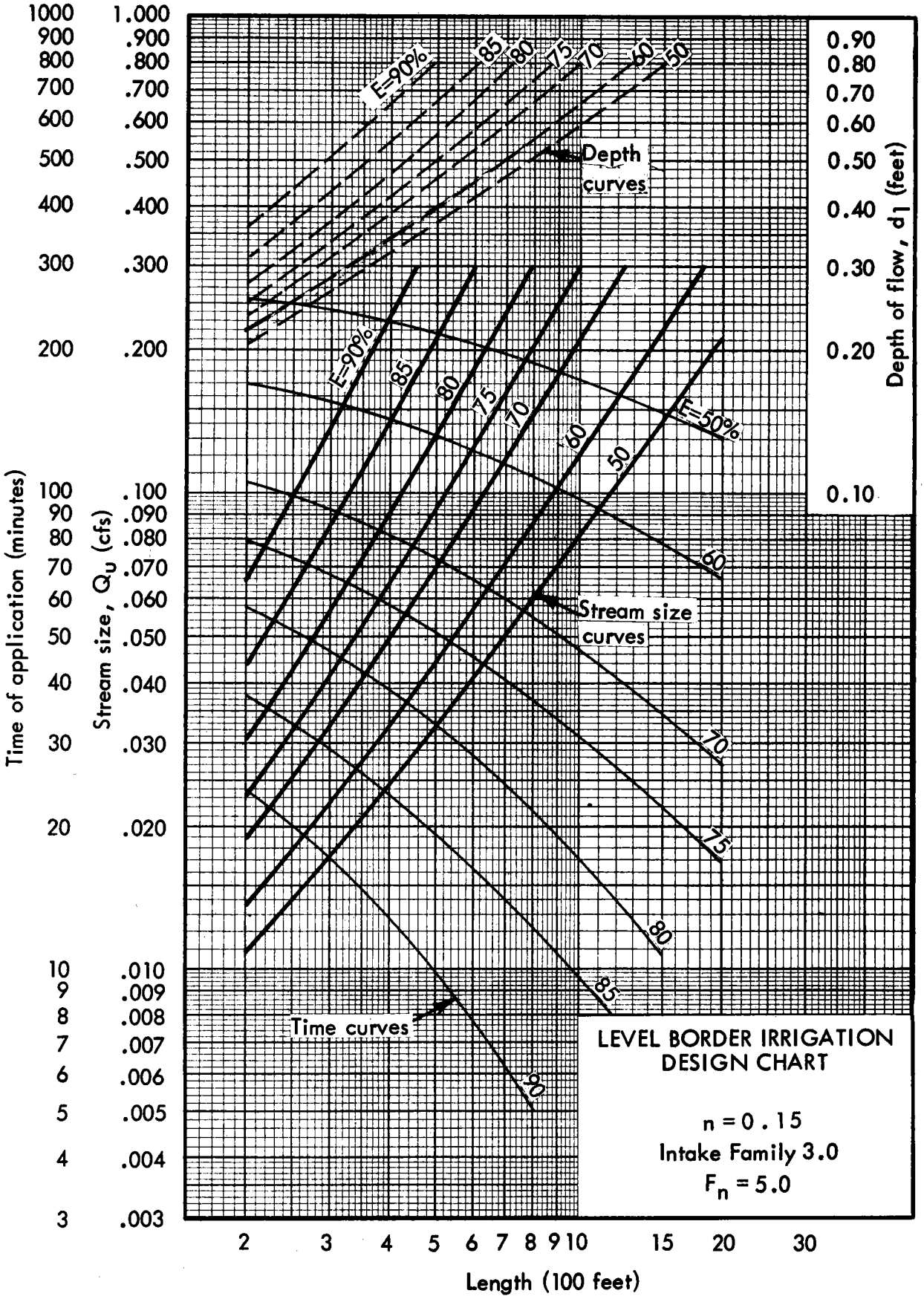

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
85
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 4.0

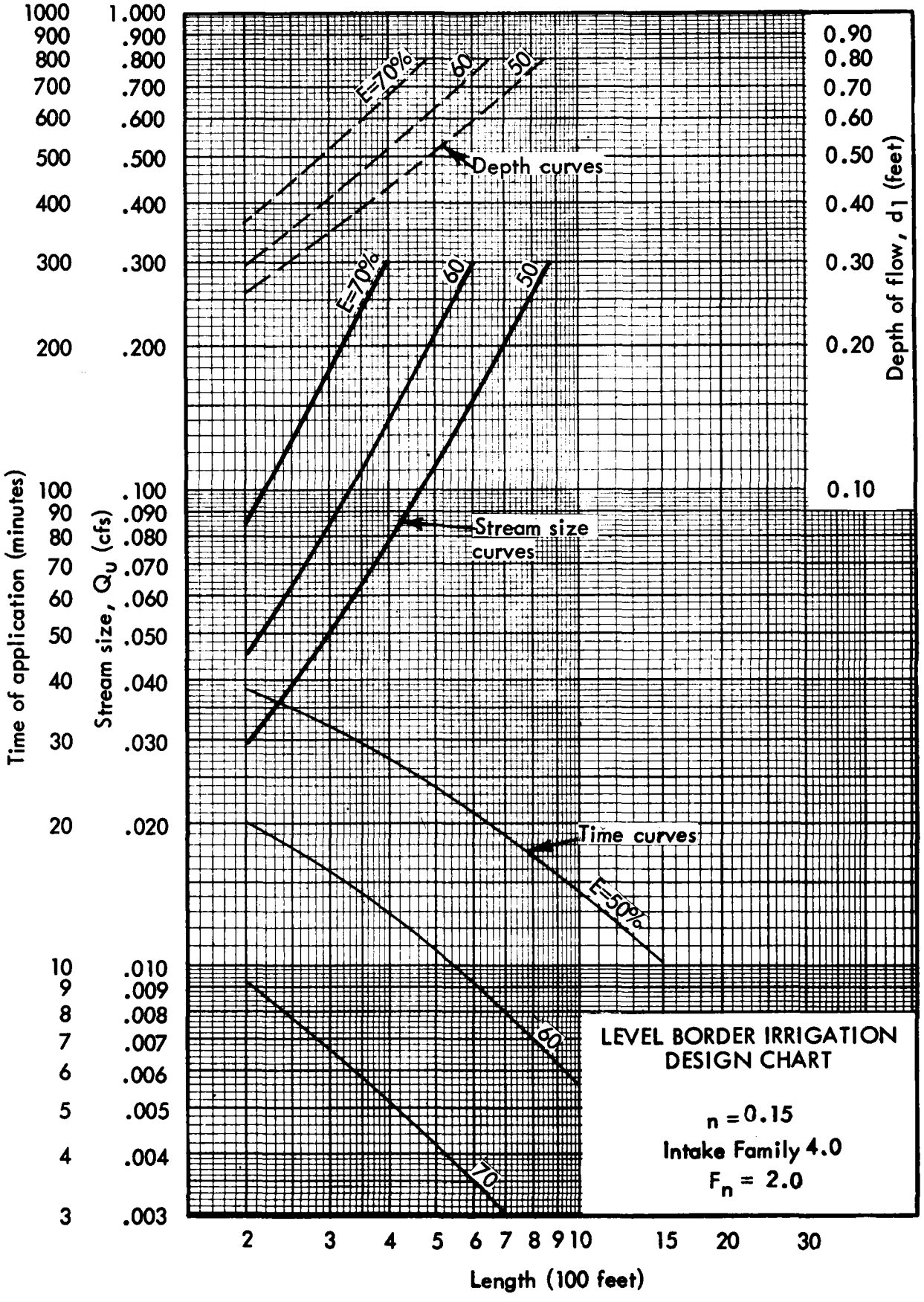

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 5.0

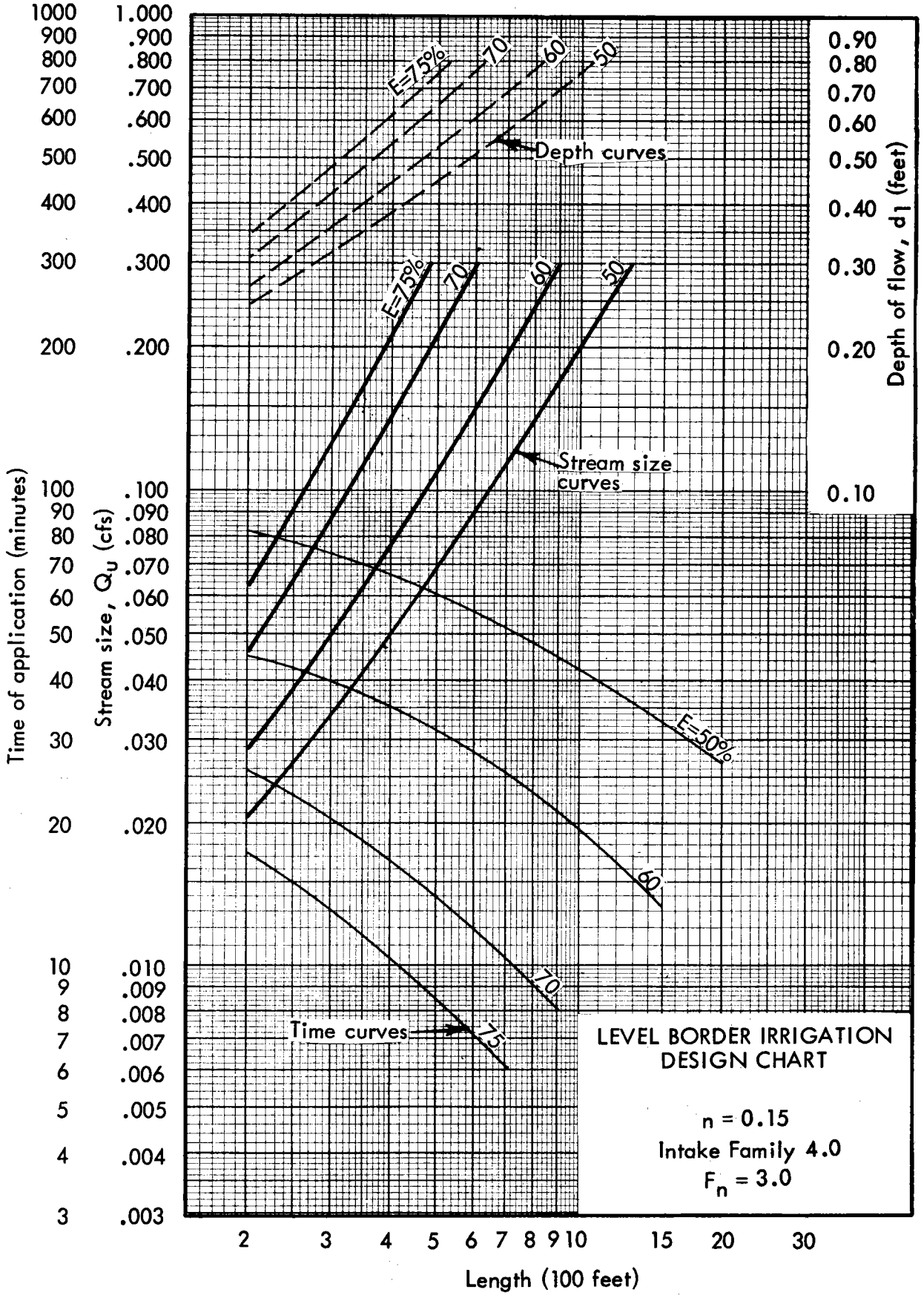

Depth curves
E=70%
60
50
Stream size curves
Time curves
E=50%
70
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 2.0

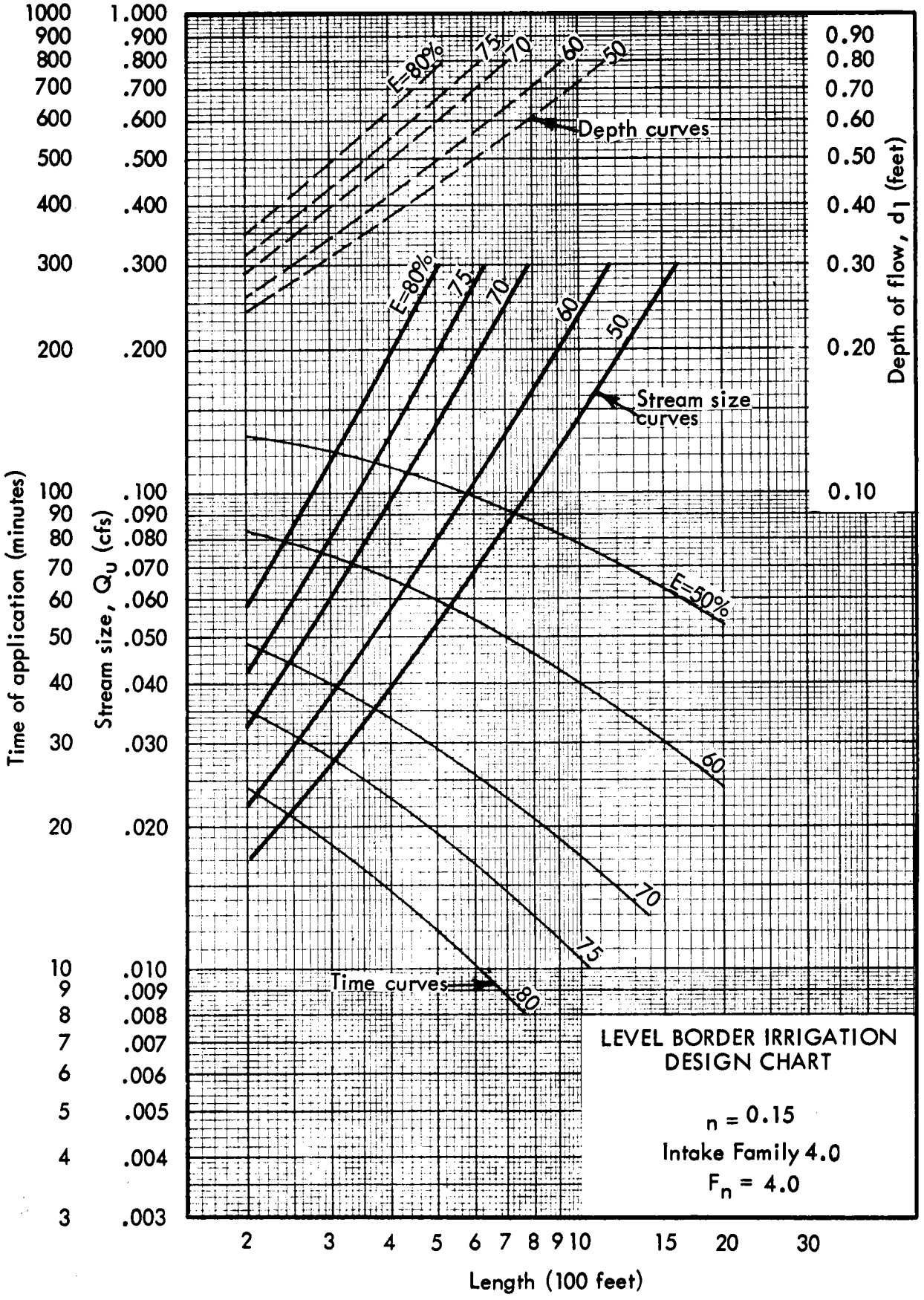

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
E=80%
75
70
60
50
Stream size curves
Time curves
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 3.0

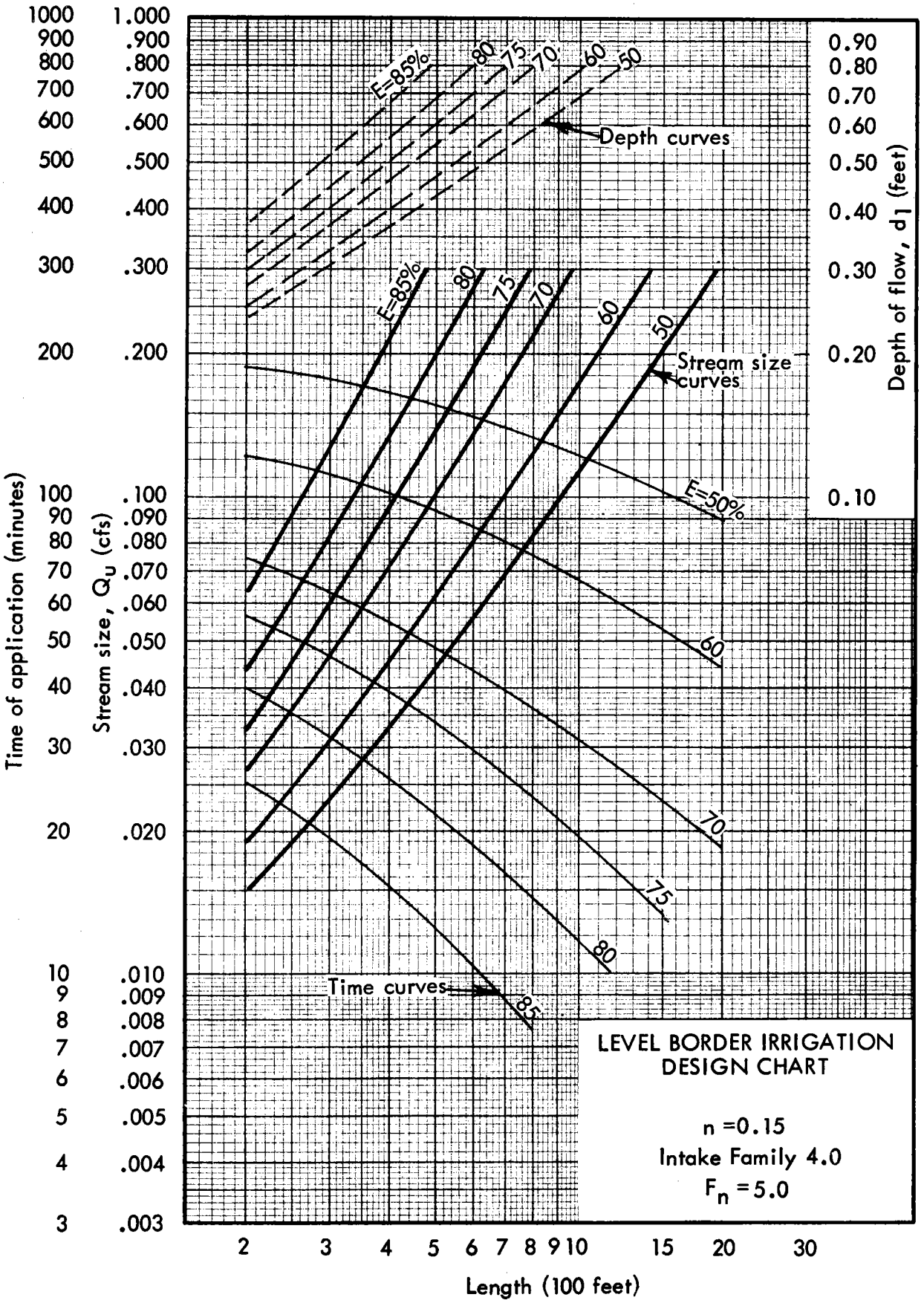

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 4.0

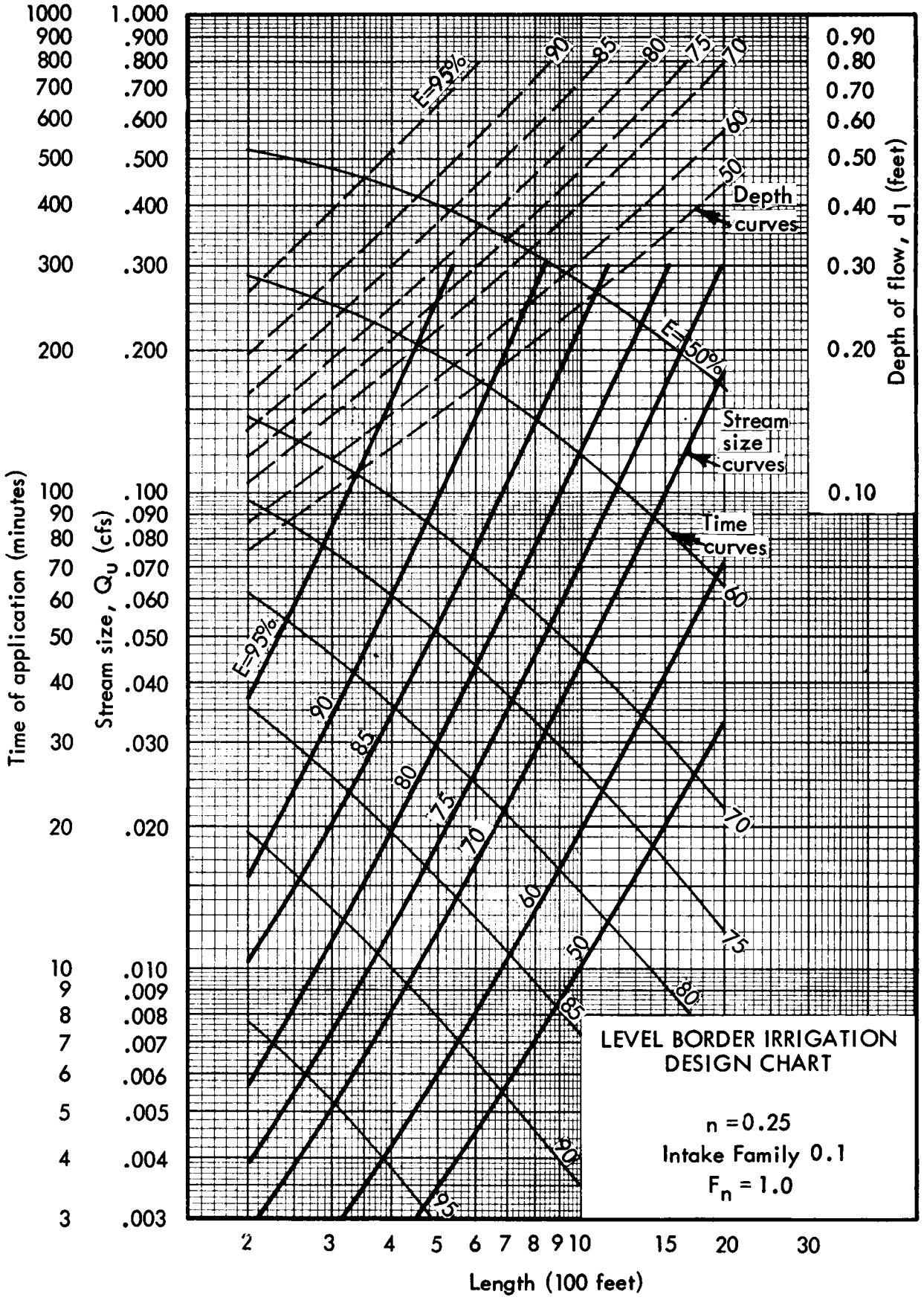

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=90%
85
80
75
70
60
50
Depth curves
Stream size curves
Time curves
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 5.0

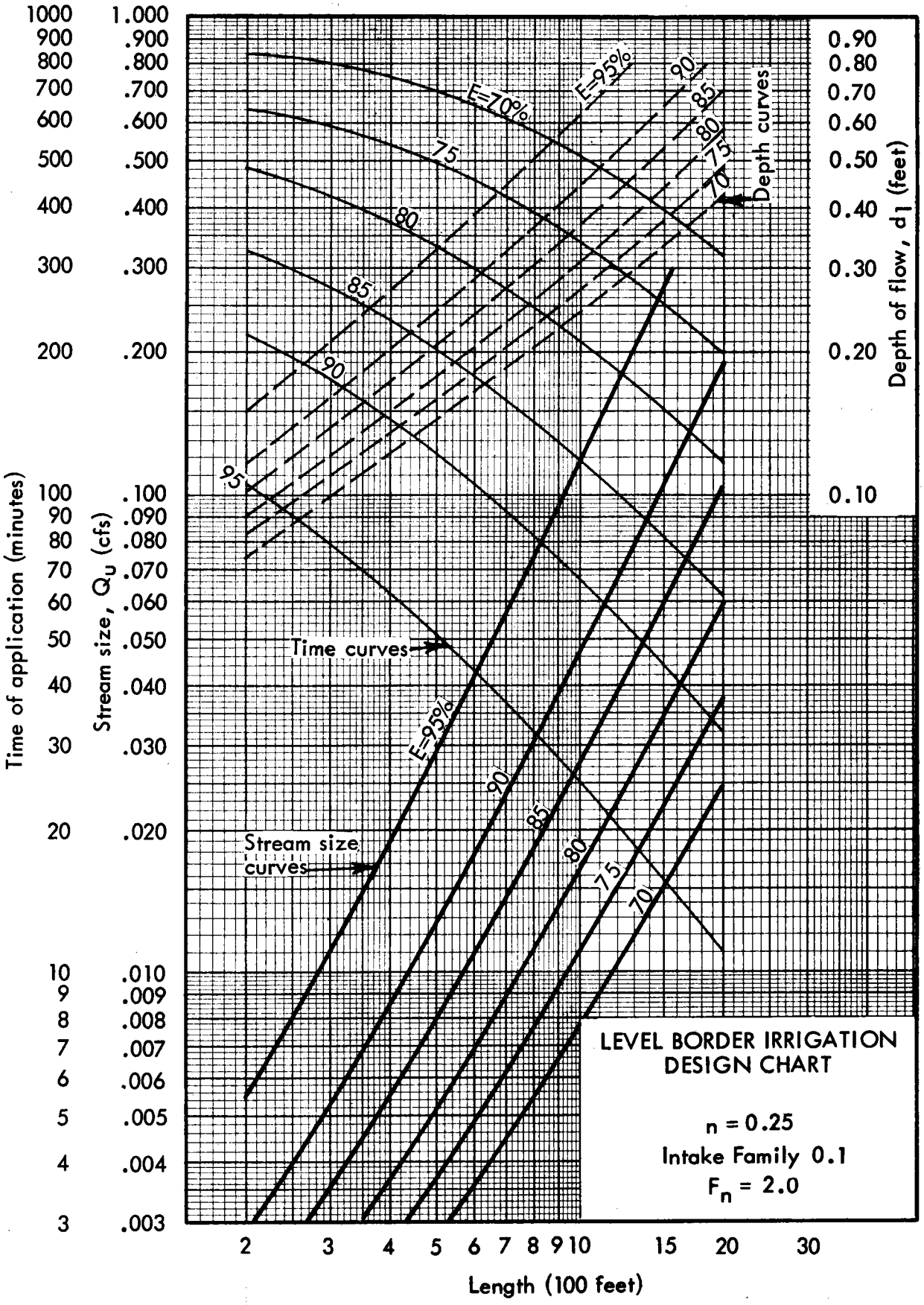

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=70%
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 2.0

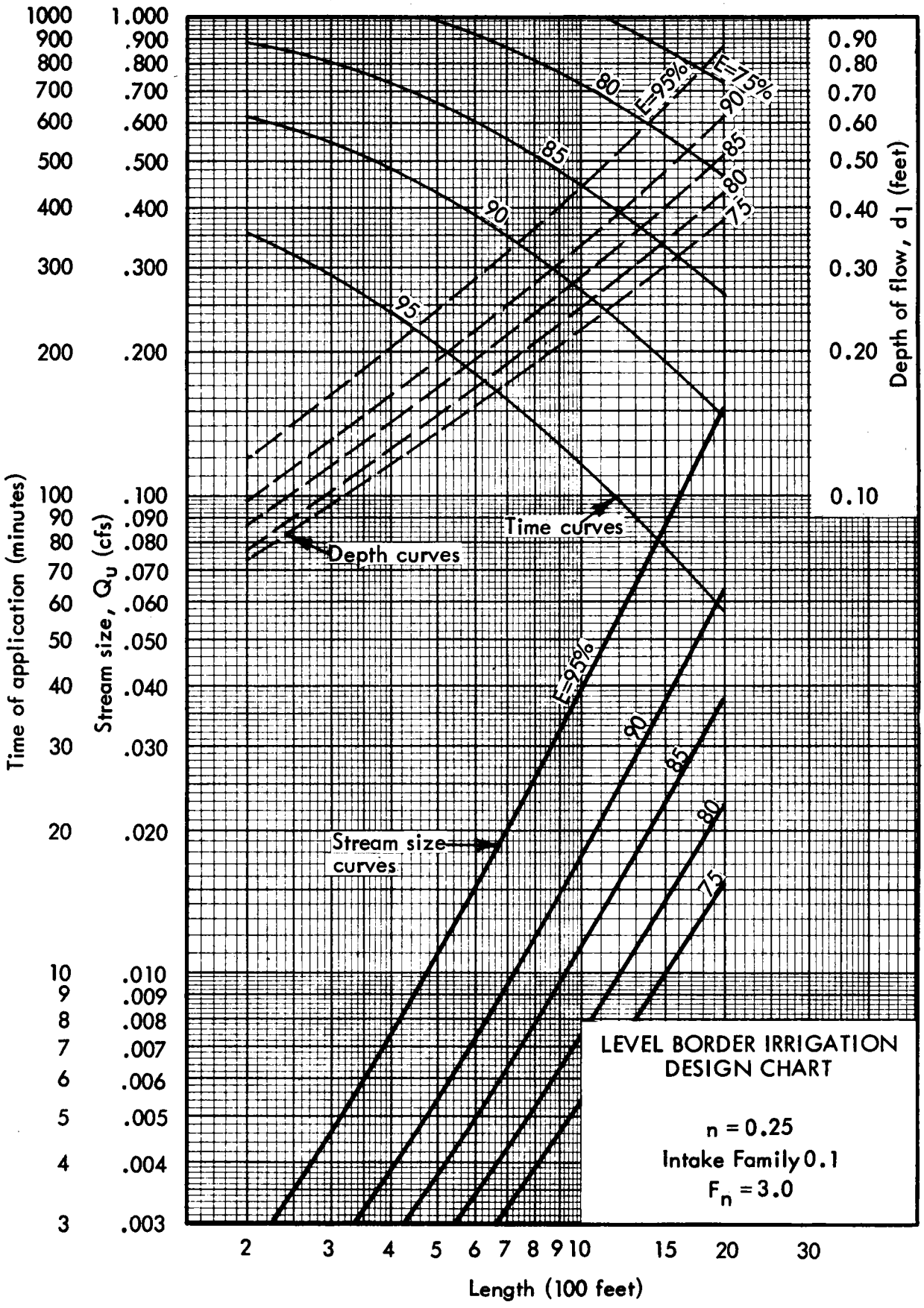

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=75%
70
60
50
Depth curves
Stream size curves
E=50%
Time curves
75
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 3.0

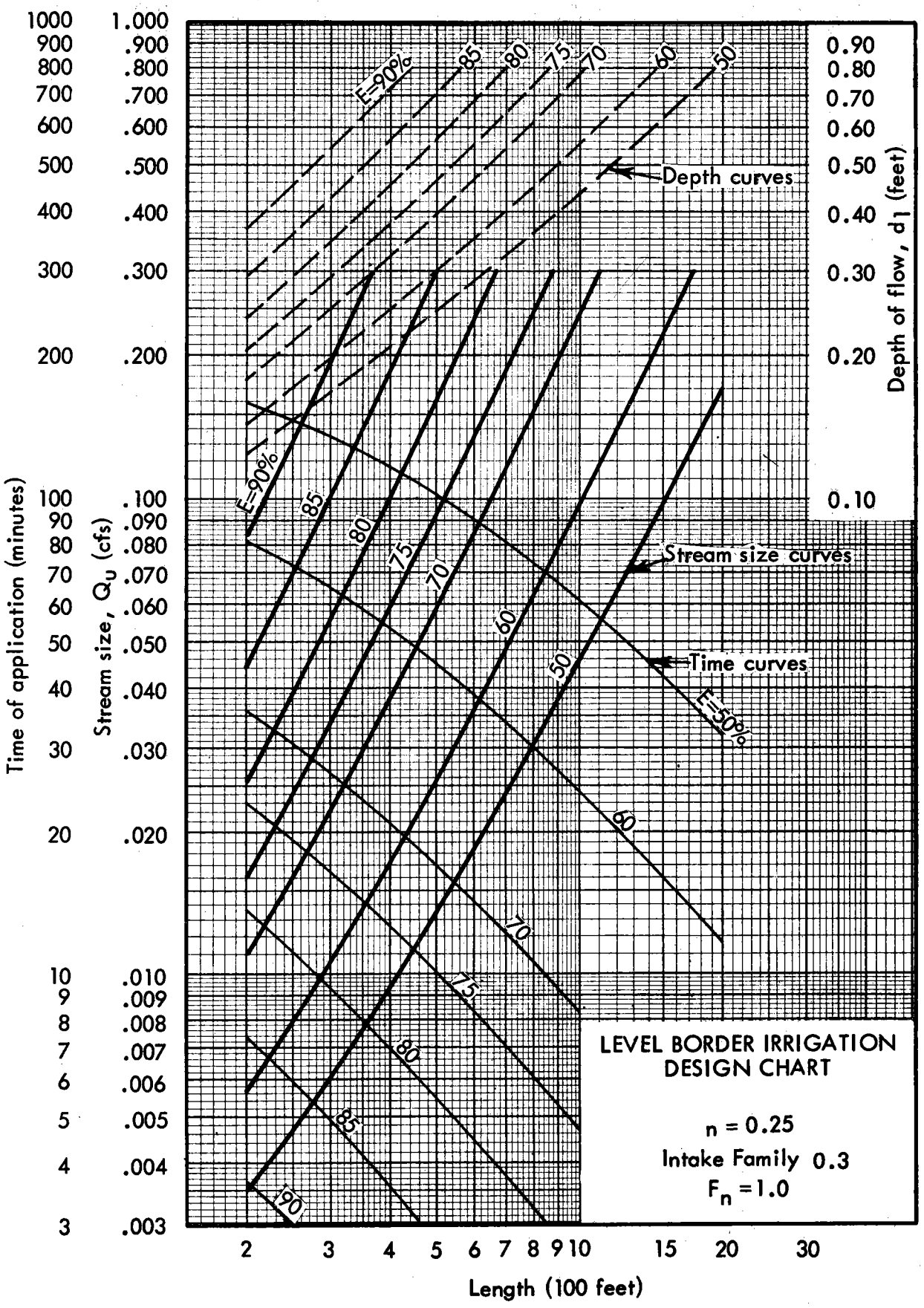

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 4.0

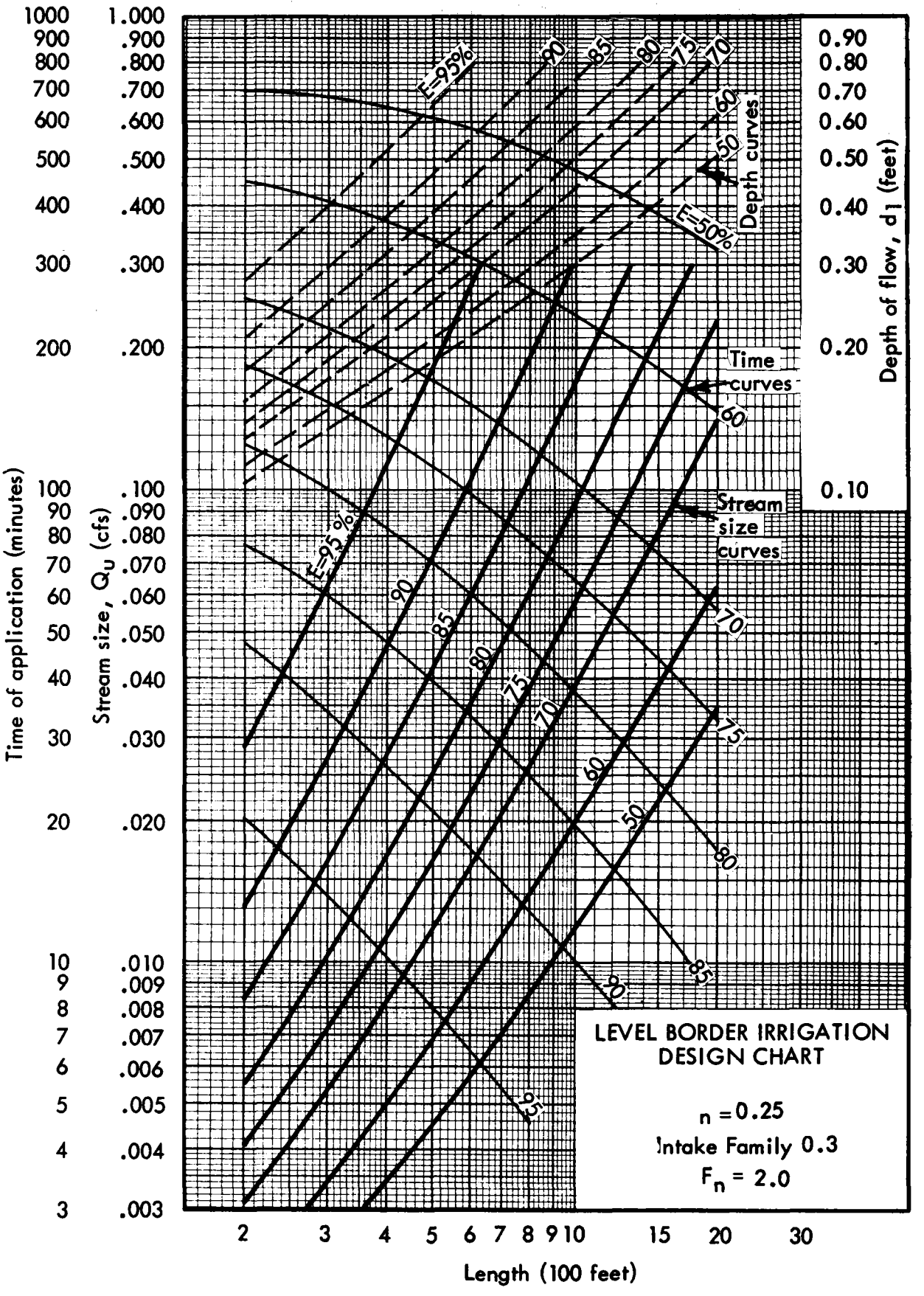

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=85%
80
75
70
60
50
Depth curves
Stream size curves
E=50%
Time curves
LEVEL BORDER IRRIGATION DESIGN CHART
n =0.15
Intake Family 4.0
F_n =5.0

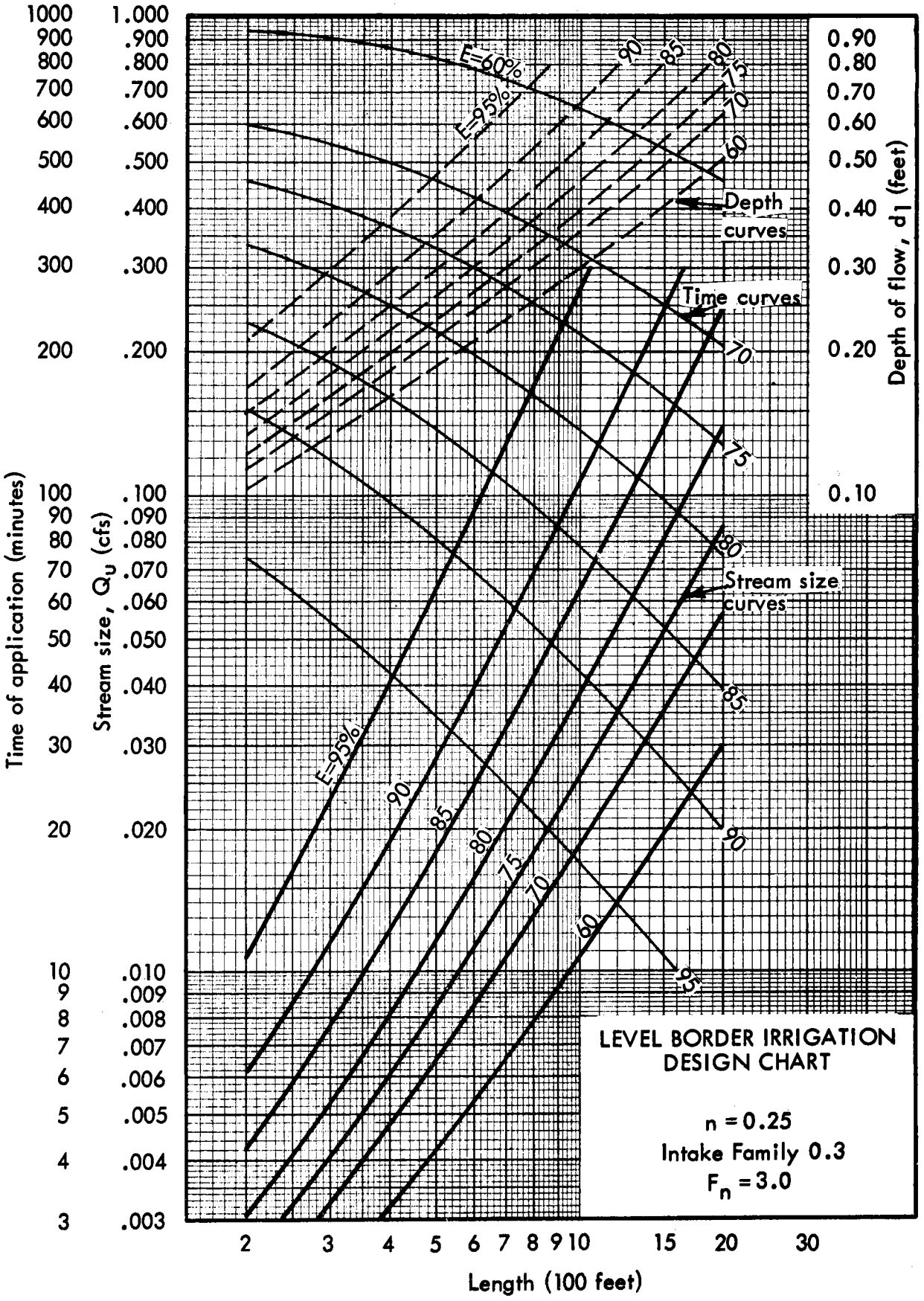

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.1
F_n = 1.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=95%
E=50%
90
85
80
75
70
60
50

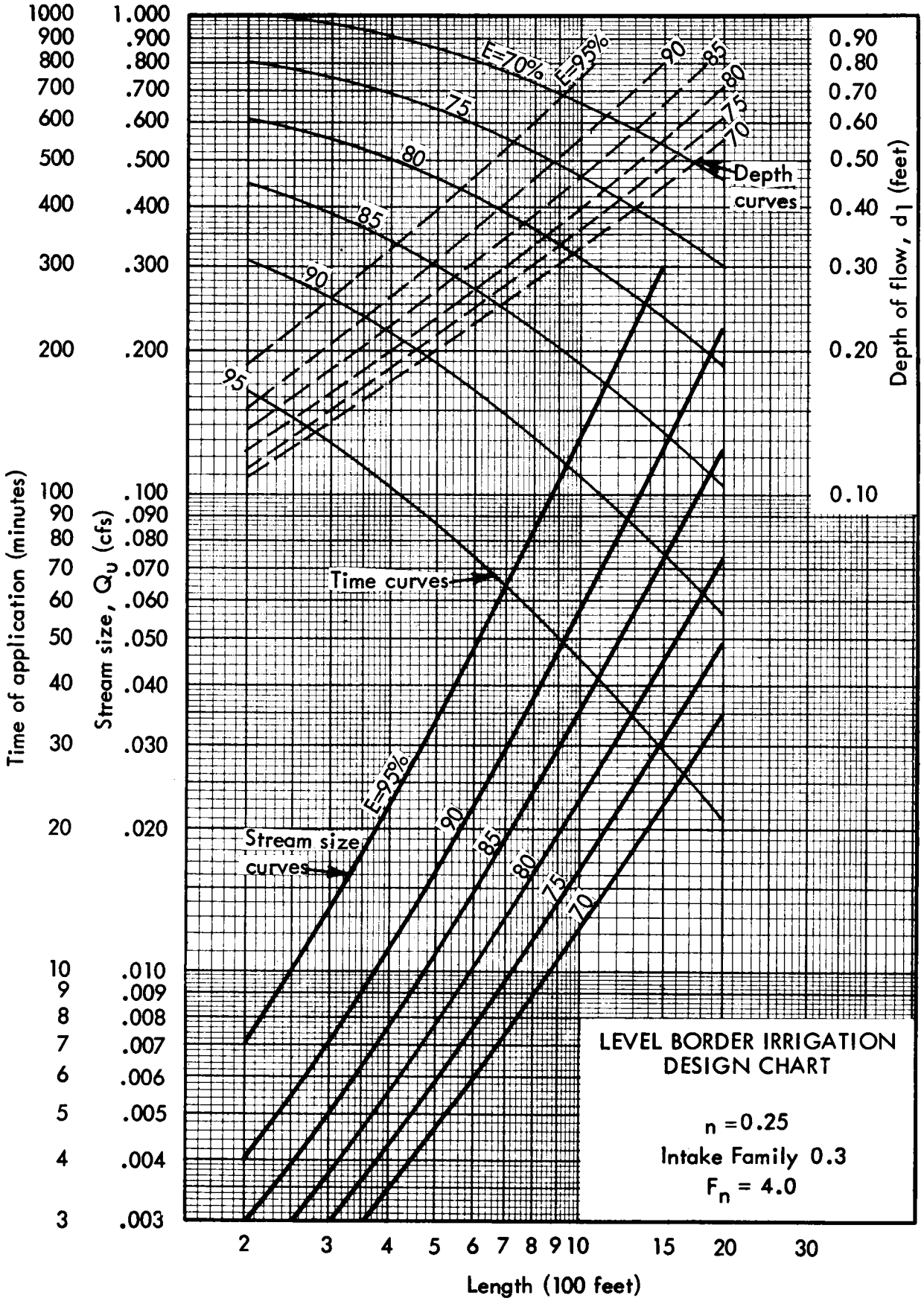

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Depth curves
Time curves
Stream size curves
E=95%
E=70%
95
90
85
80
75
70
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.1
F_n = 2.0
Length (100 feet)

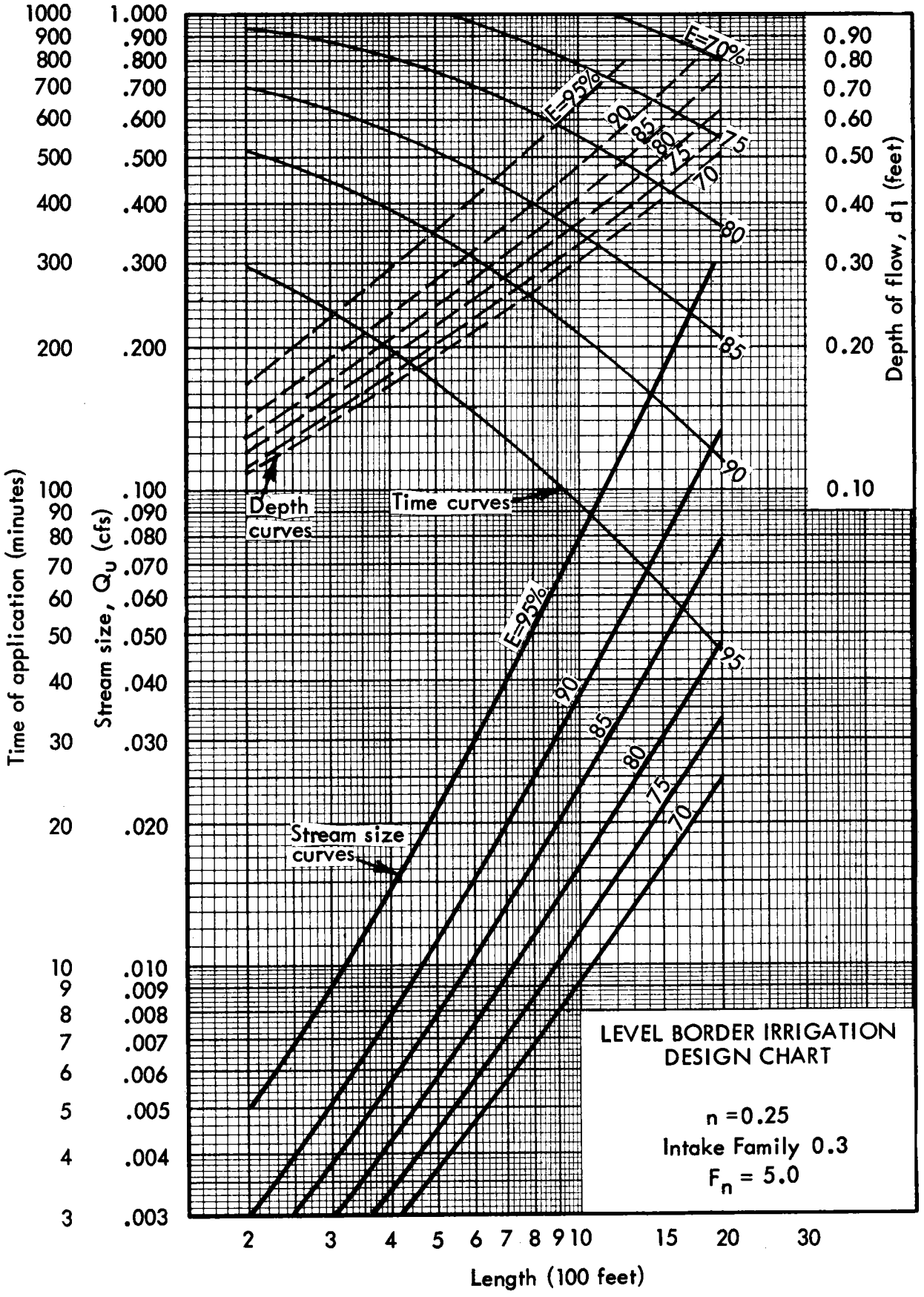

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=95%
E=75%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.1
F_n = 3.0

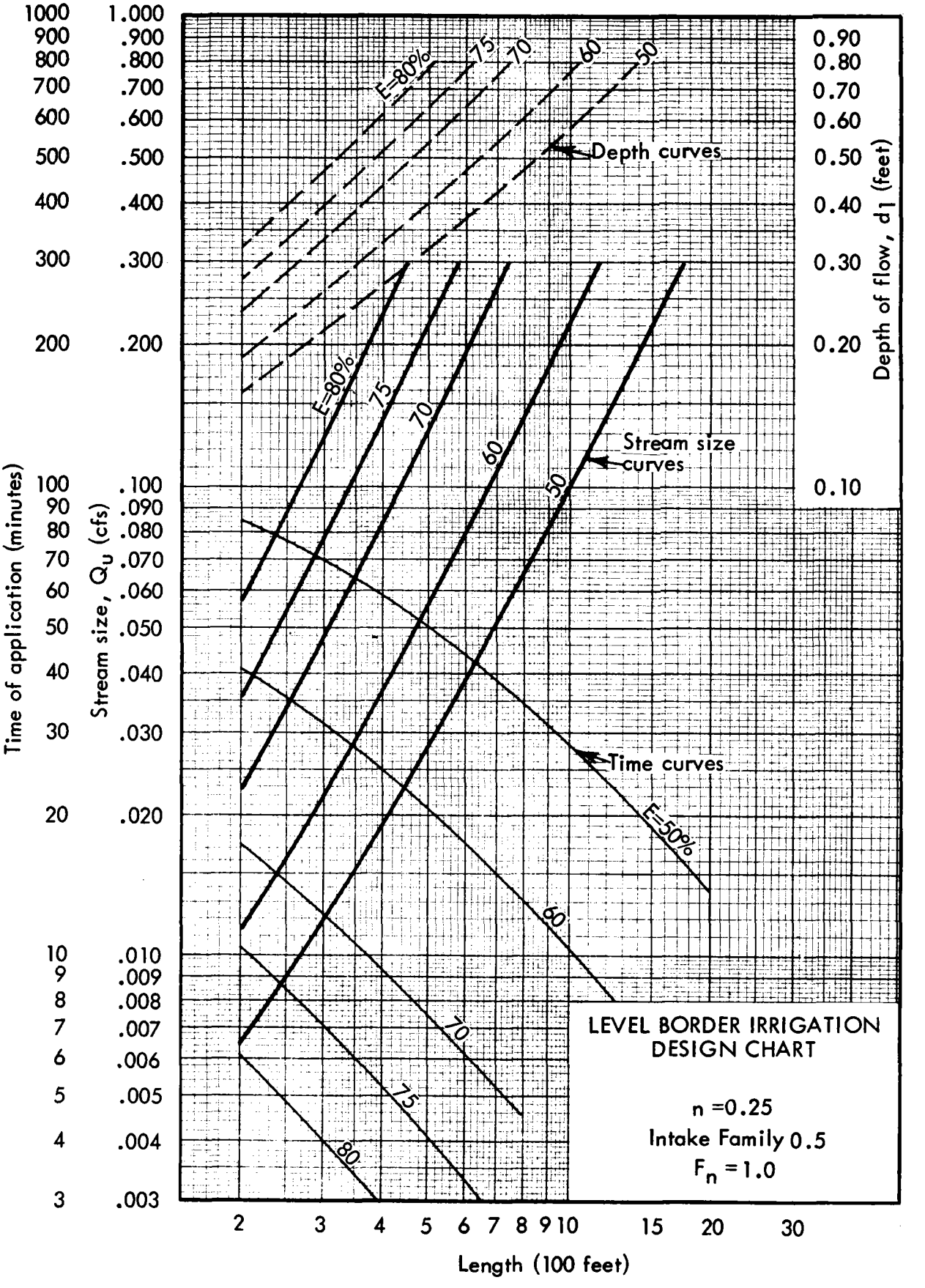

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 1.0

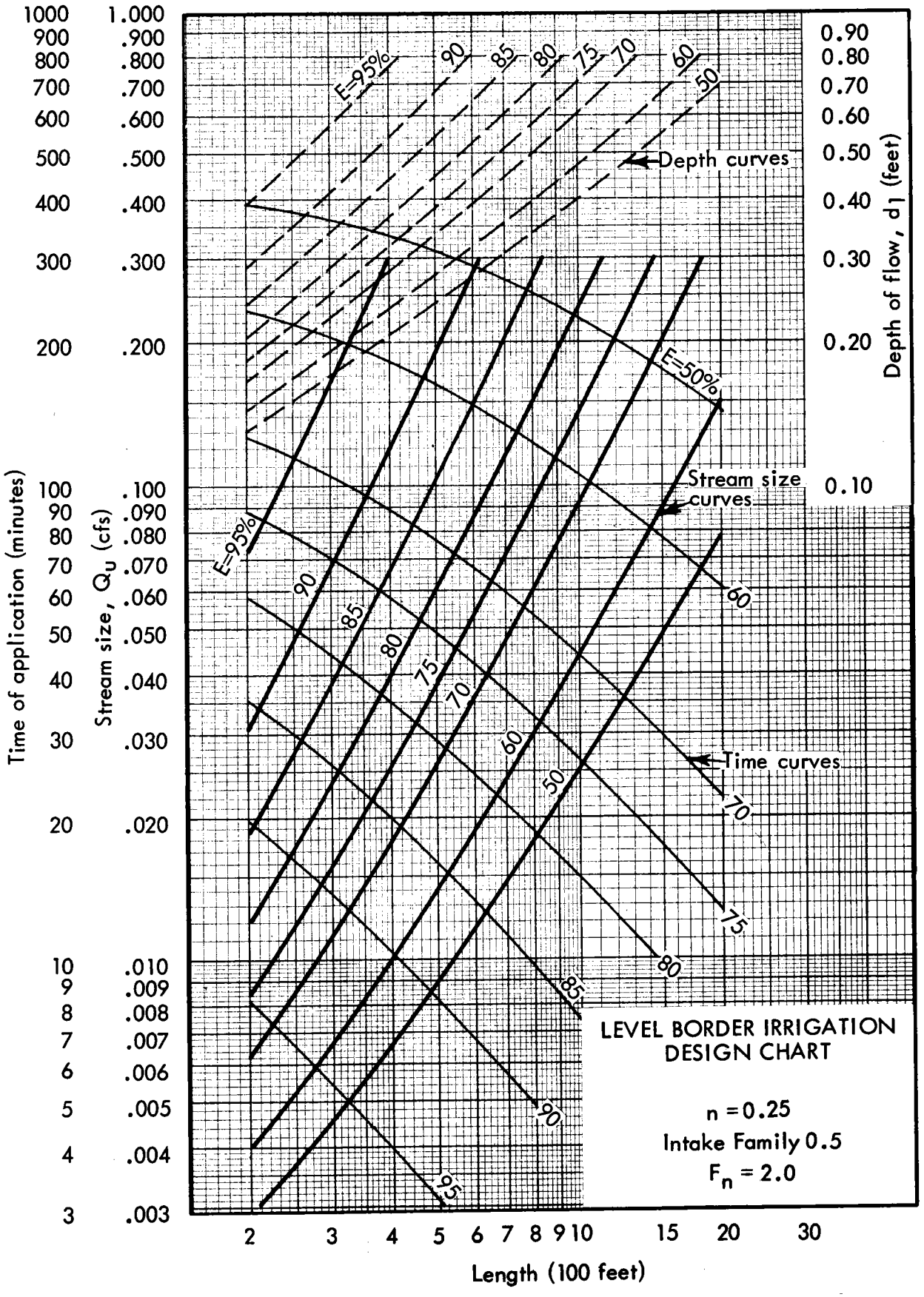

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 2.0

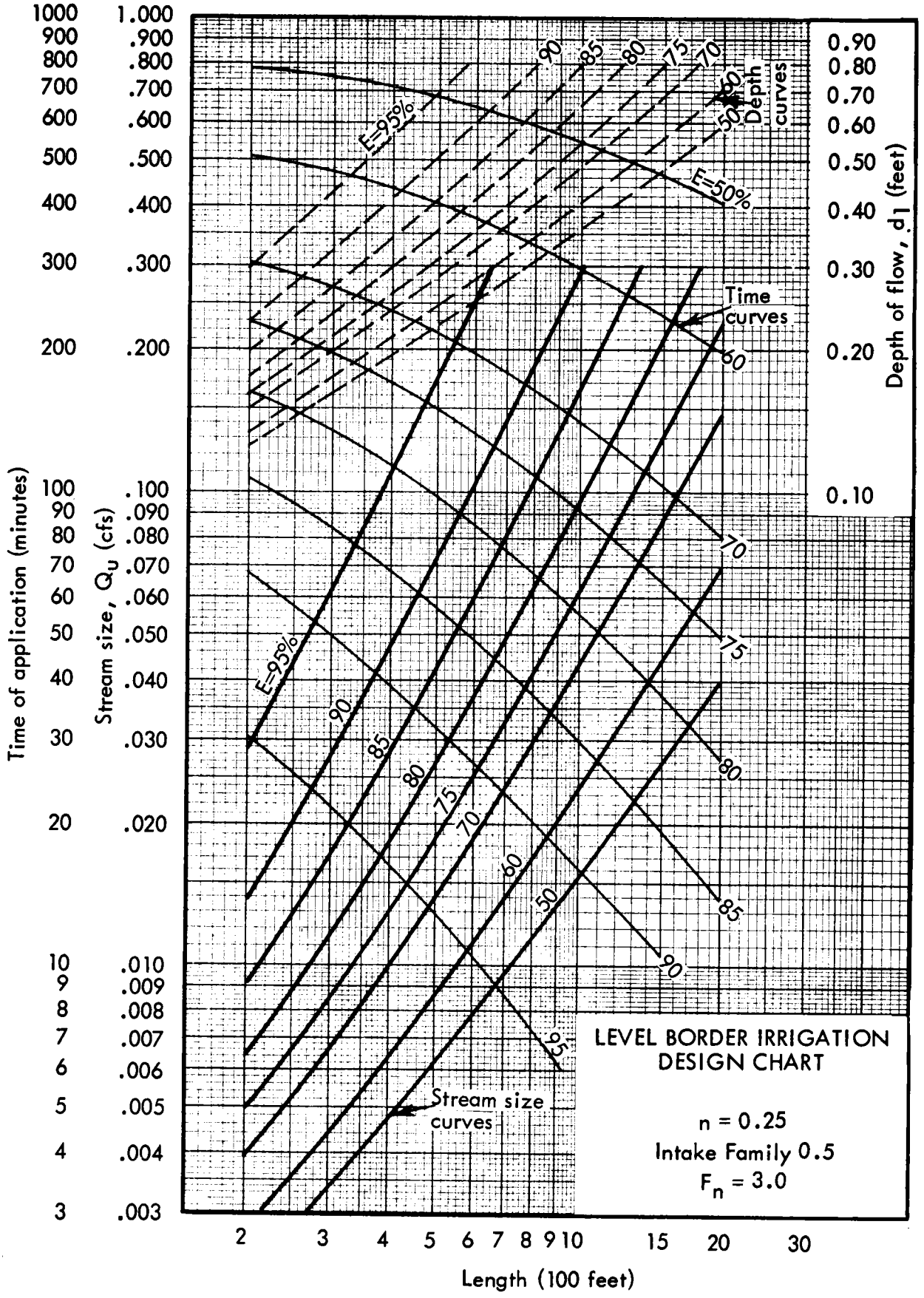

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 3.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=60%
E=95%
90
85
80
75
70
60
95

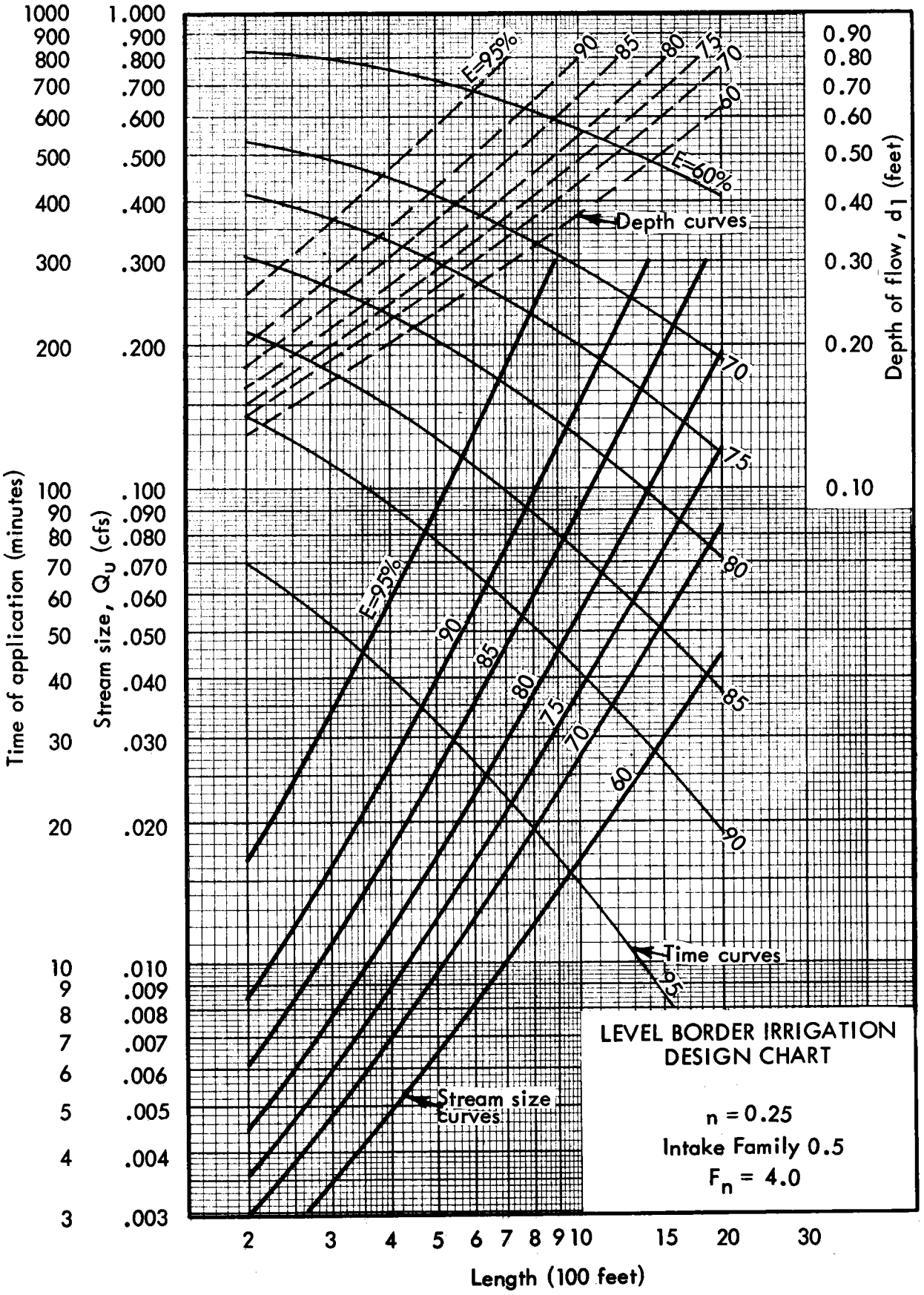

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
E=70%
E=95%
75
80
85
90
95
Depth curves
Time curves
Stream size curves
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 4.0

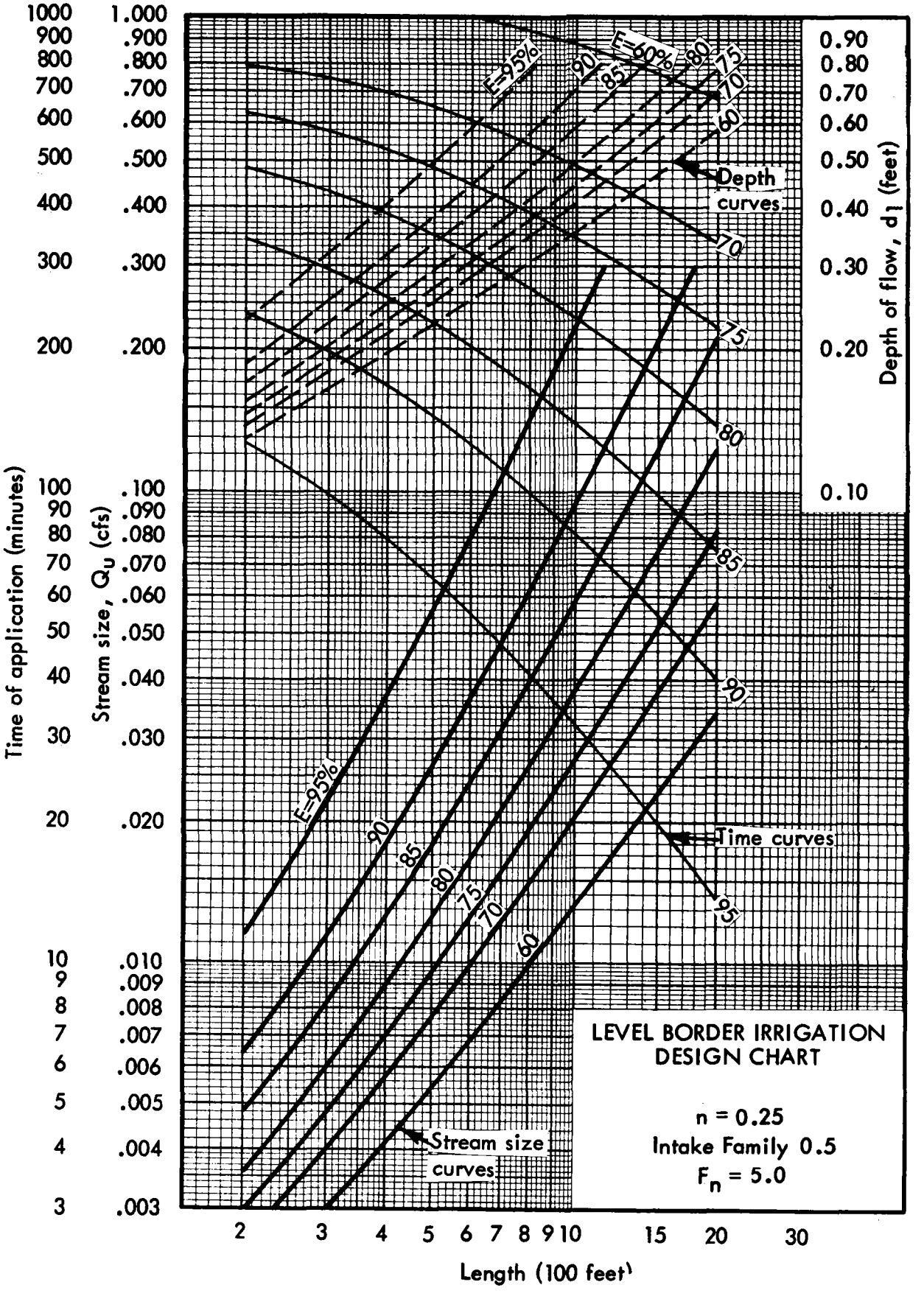

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=70%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 5.0

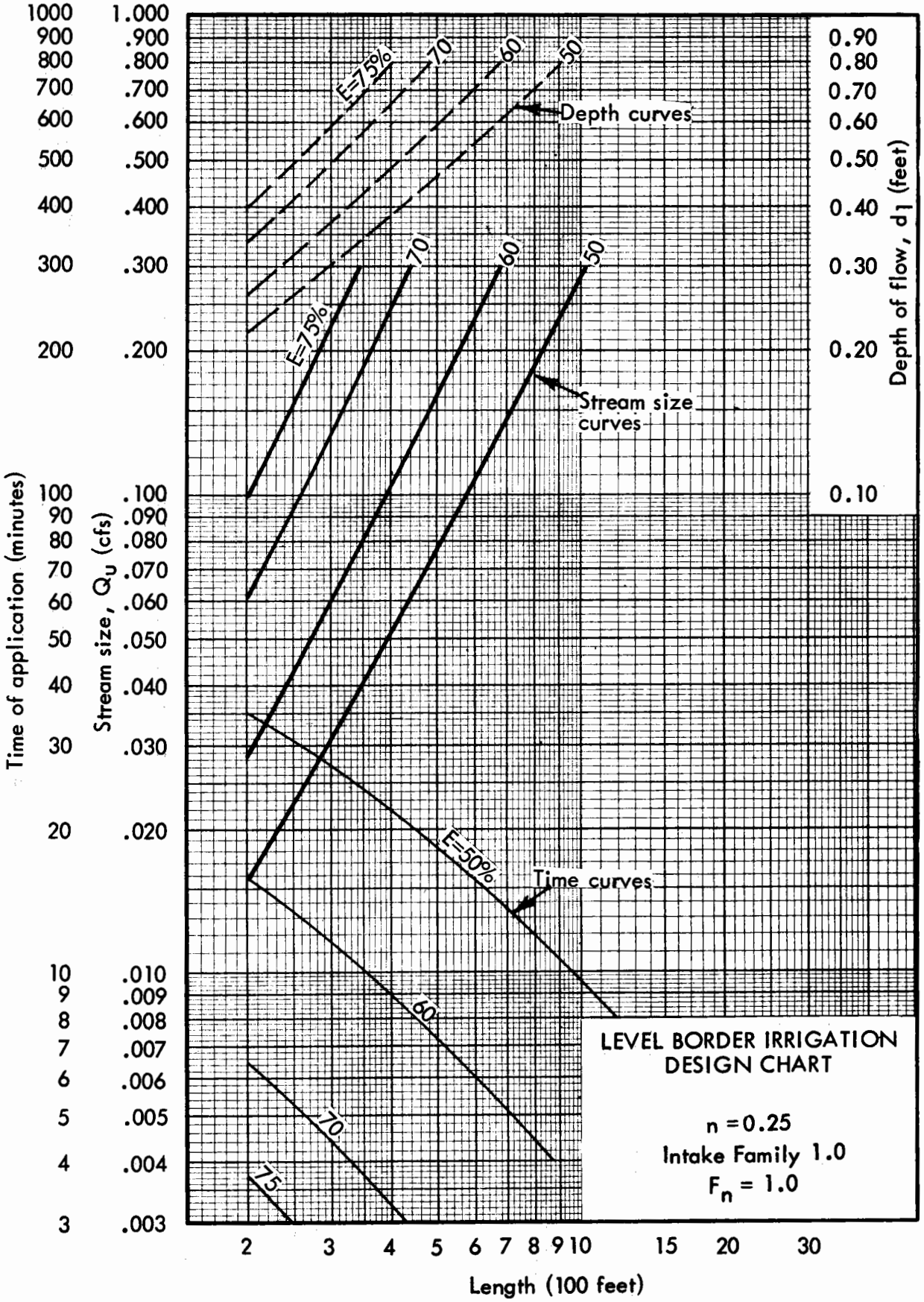

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
80
LEVEL BORDER IRRIGATION DESIGN CHART
n =0.25
Intake Family 0.5
F_n =1.0

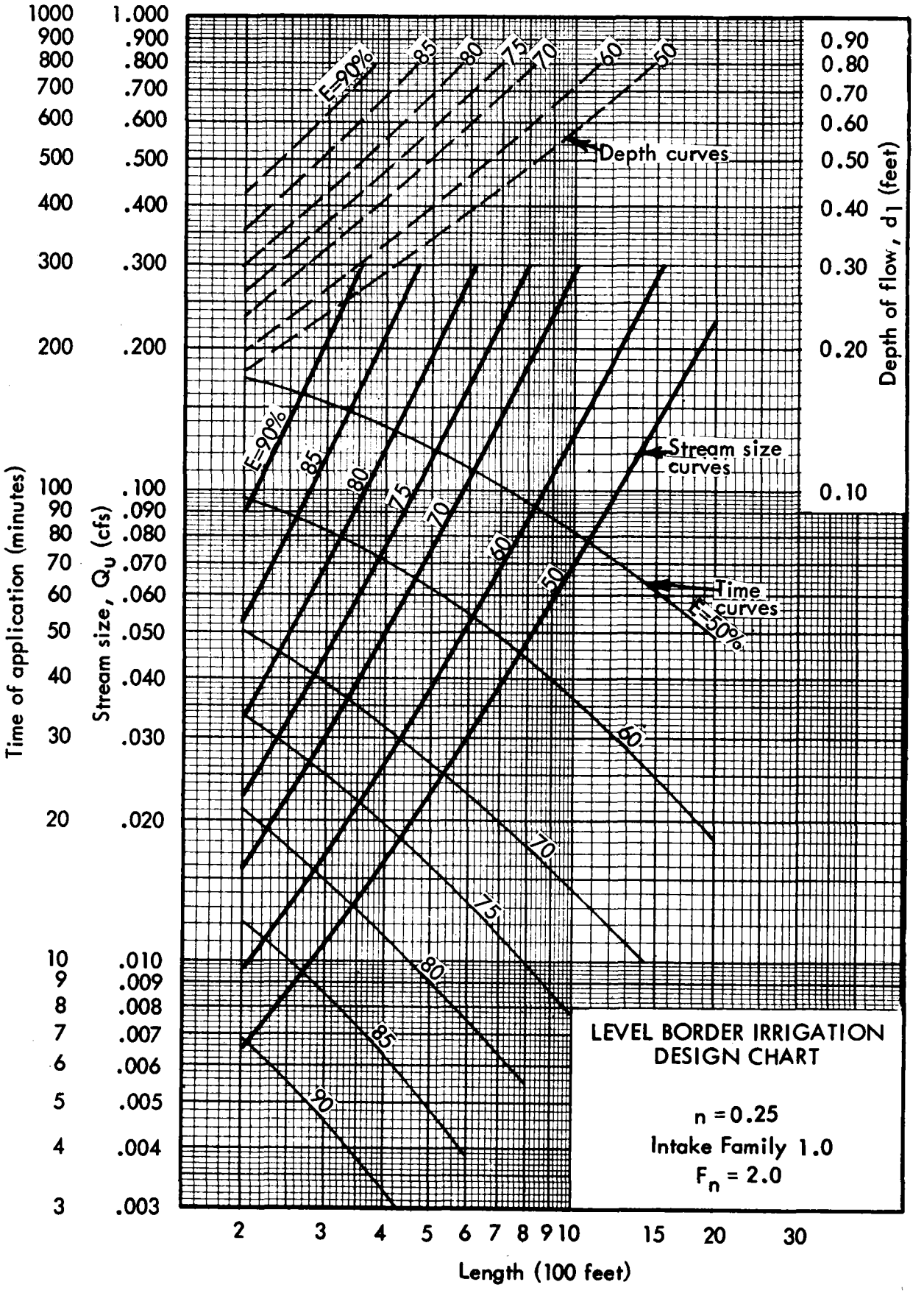

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 2.0
Depth curves
Stream size curves
Time curves
E=95%
E=50%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)

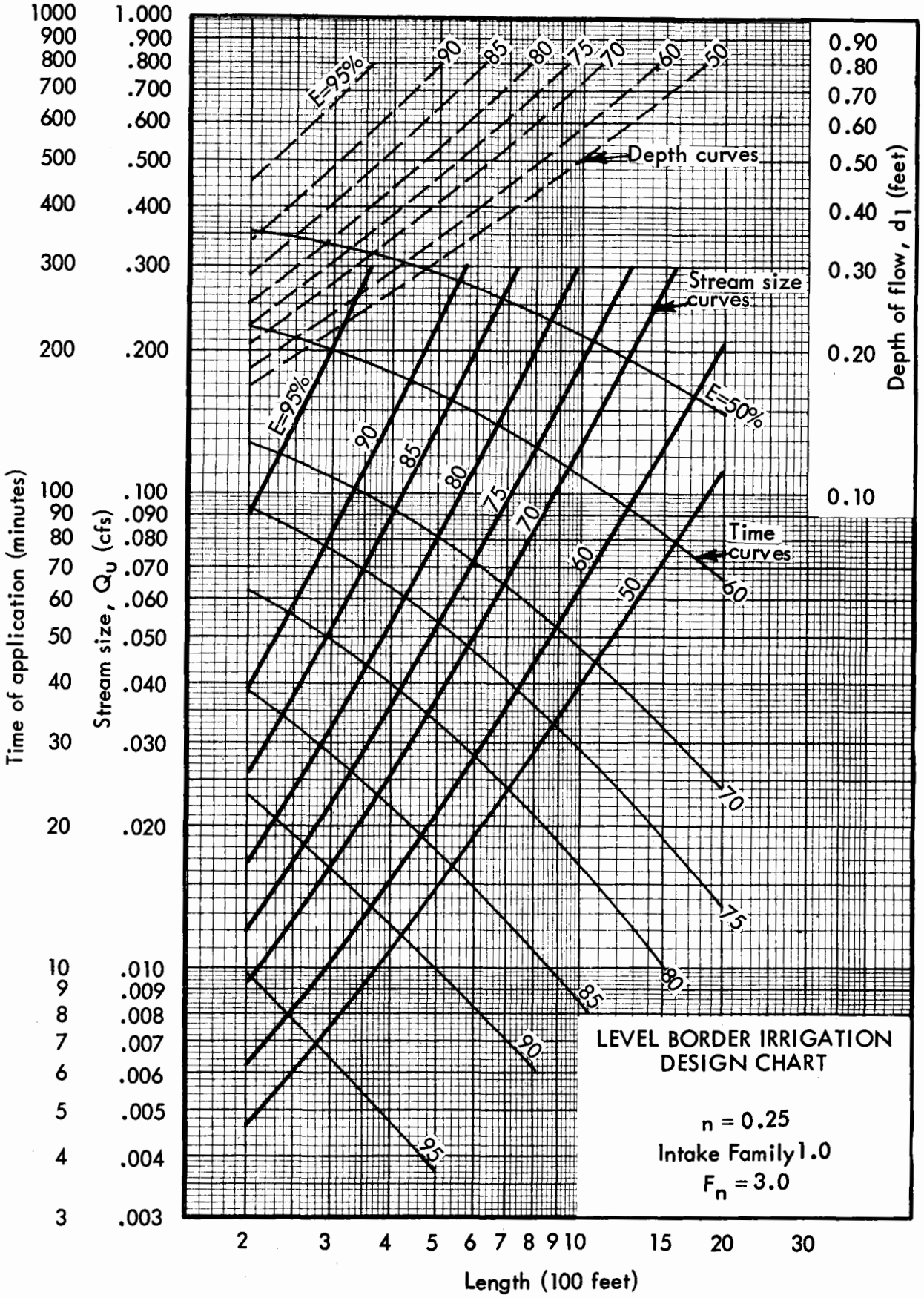

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 3.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Time curves
Depth curves
Stream size curves
E=95%
E=50%
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2
3
4
5
6
7
8
9
10
15
20
30

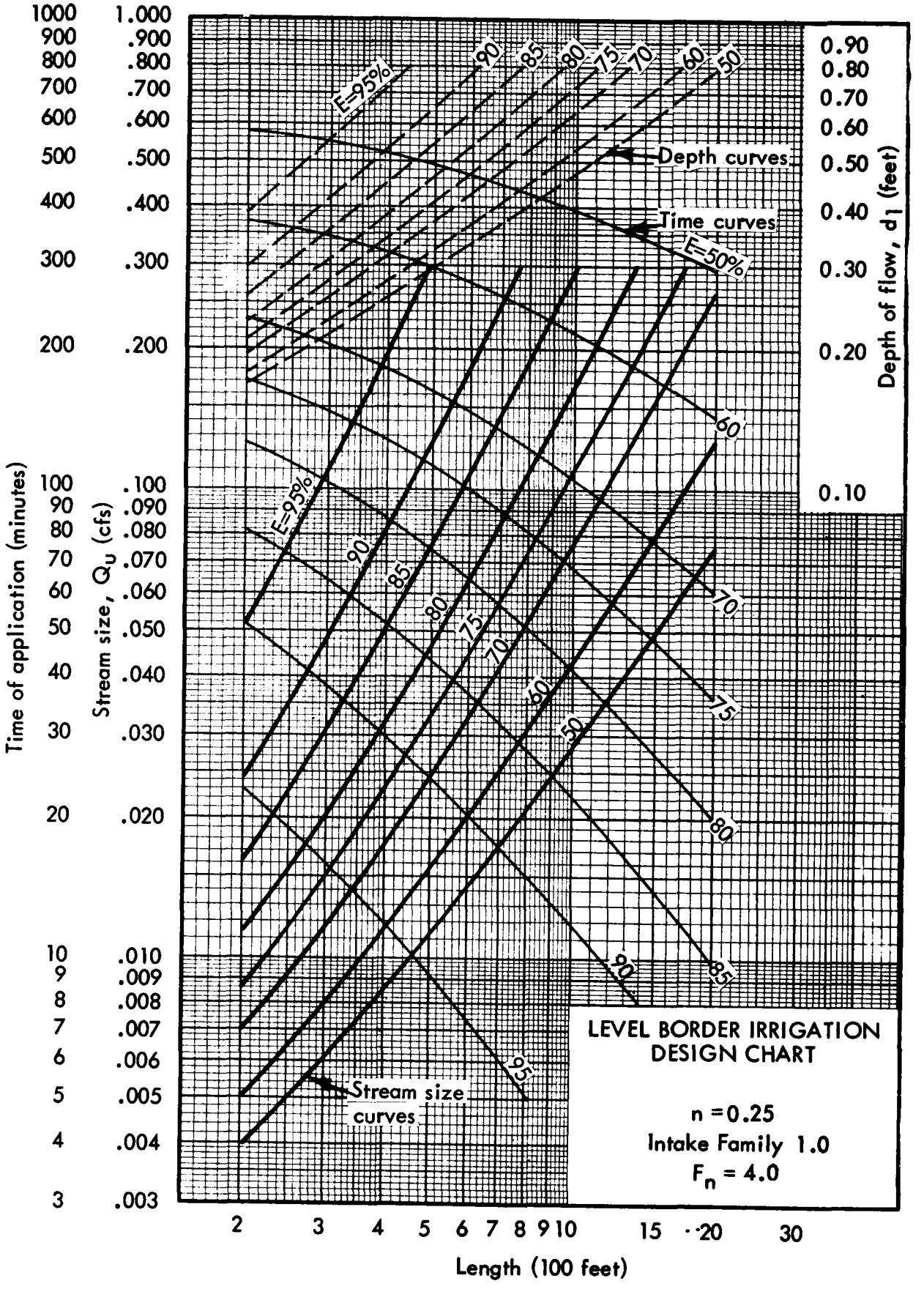

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 4.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=60%
90
85
80
75
70
60
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2
3
4
5
6
7
8
9
10
15
20
30

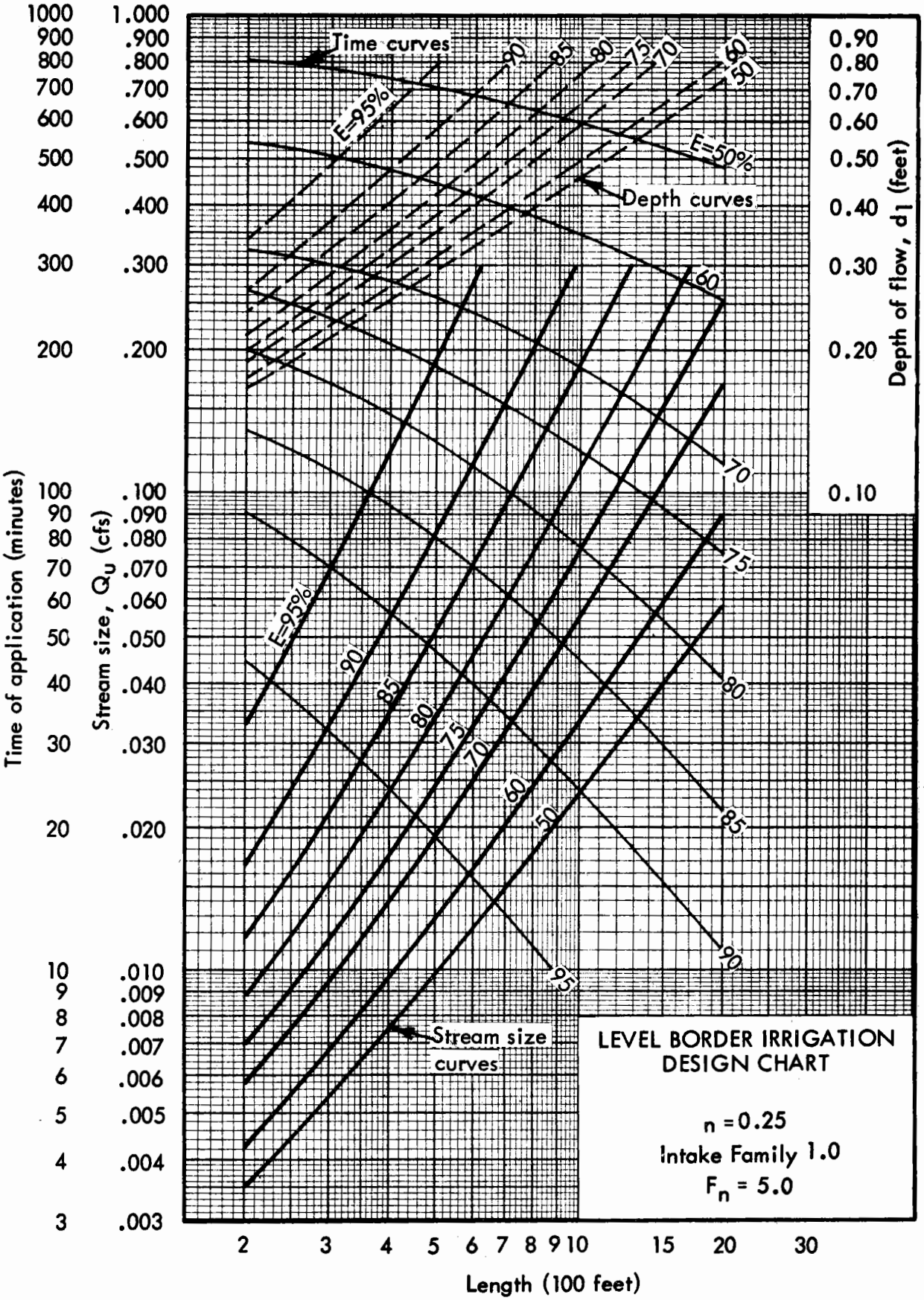

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 5.0

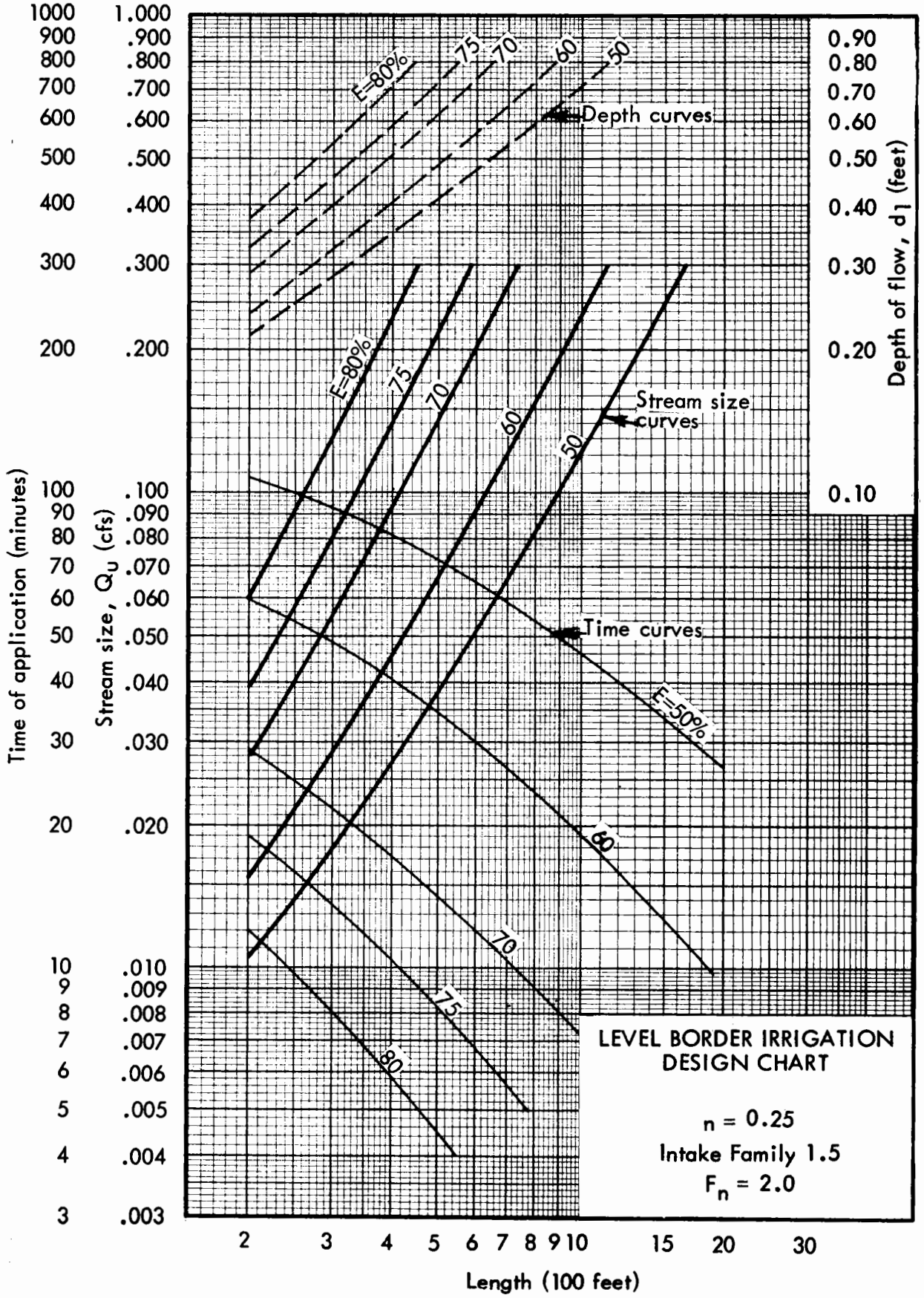

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=75%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 1.0

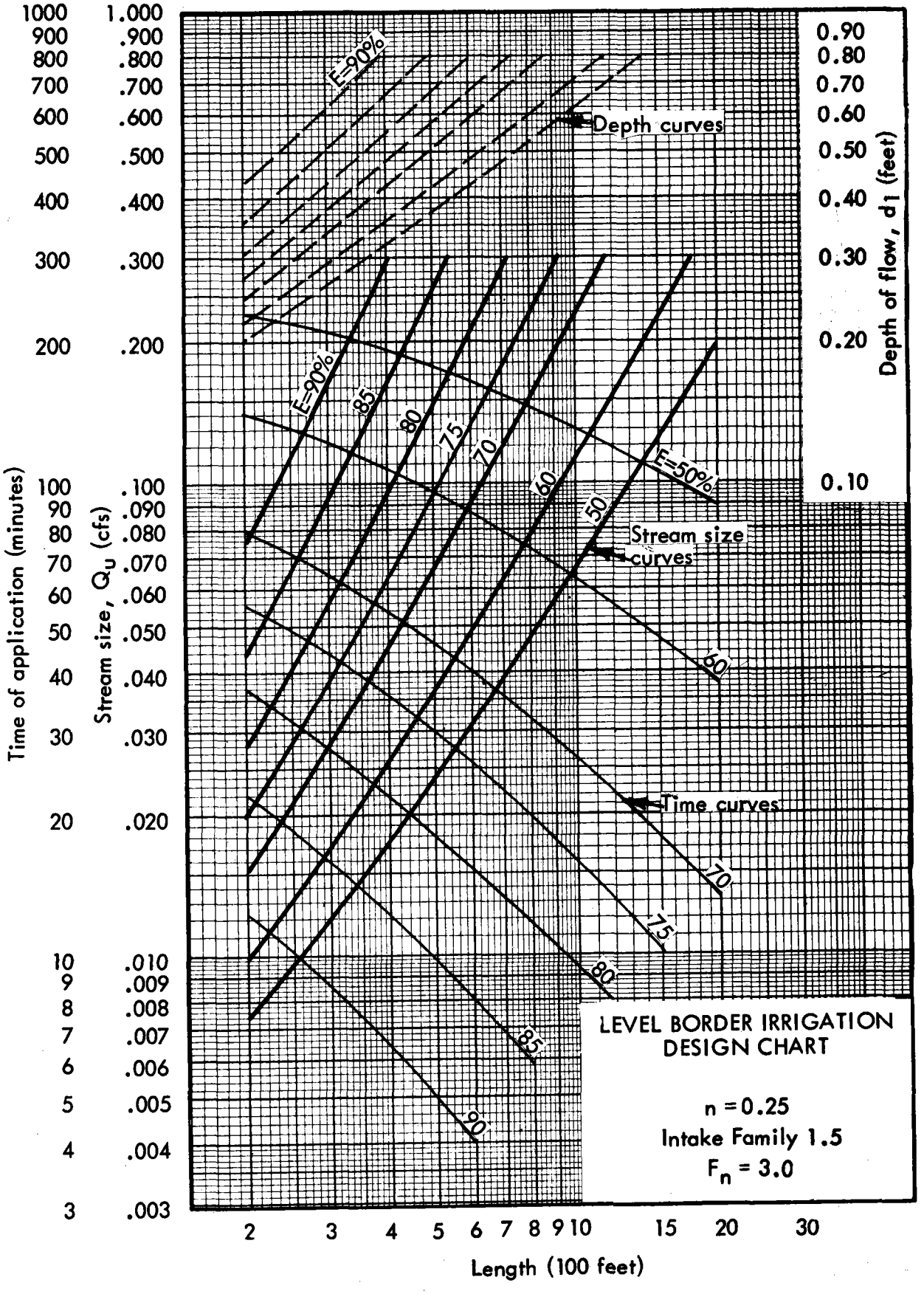

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 2.0

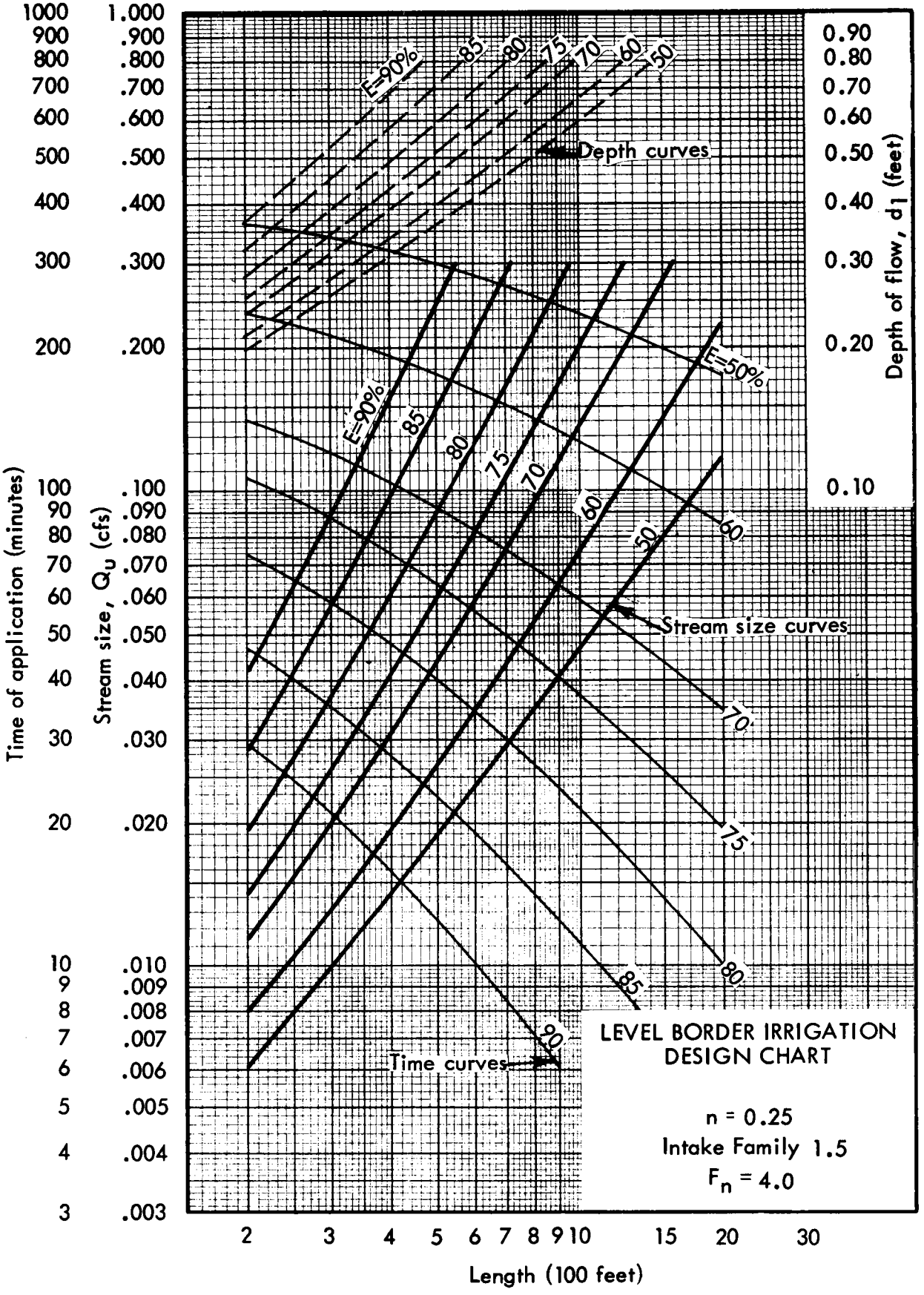

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=95%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 3.0

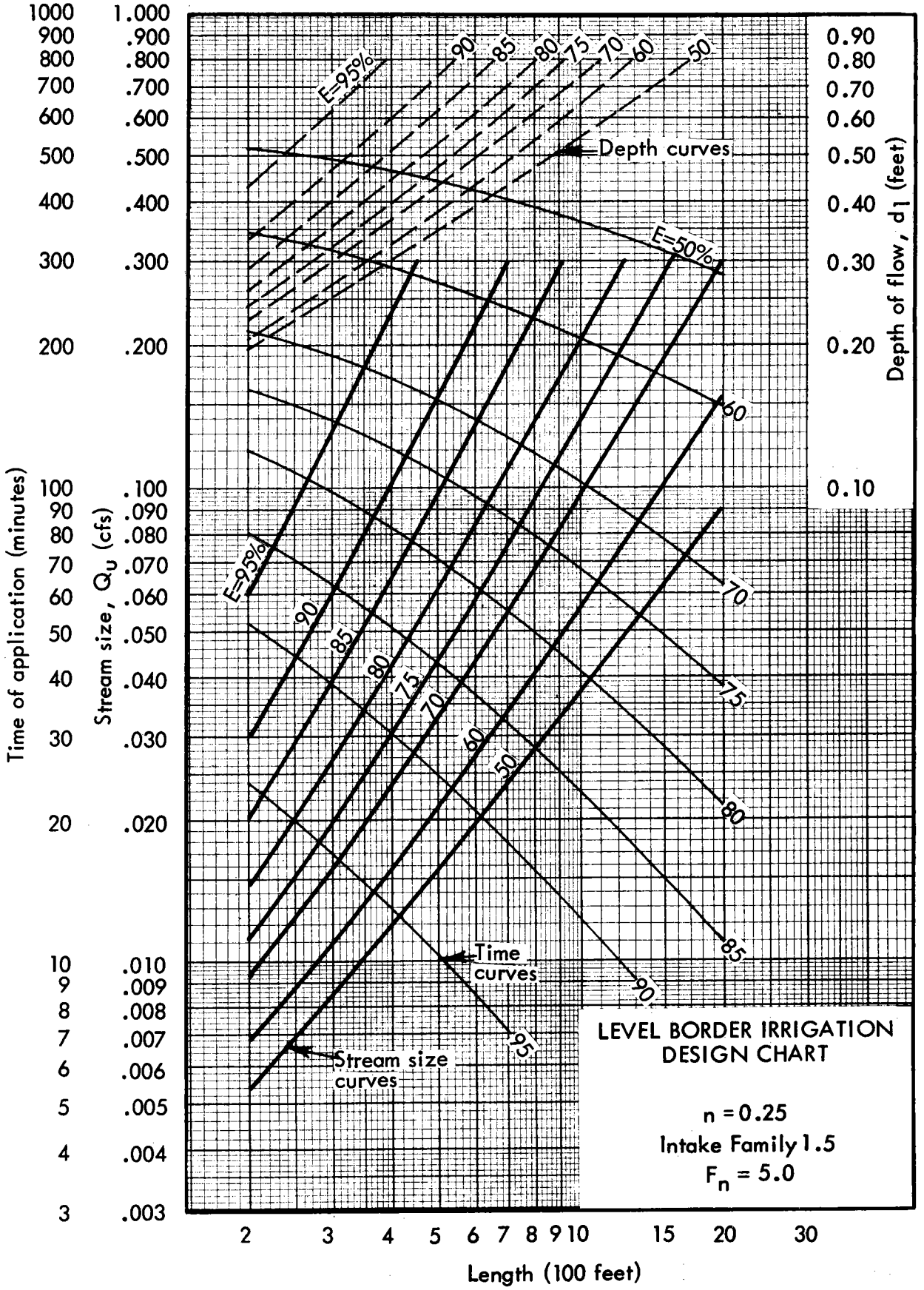

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 4.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
90
85
80
75
70
60
50
65

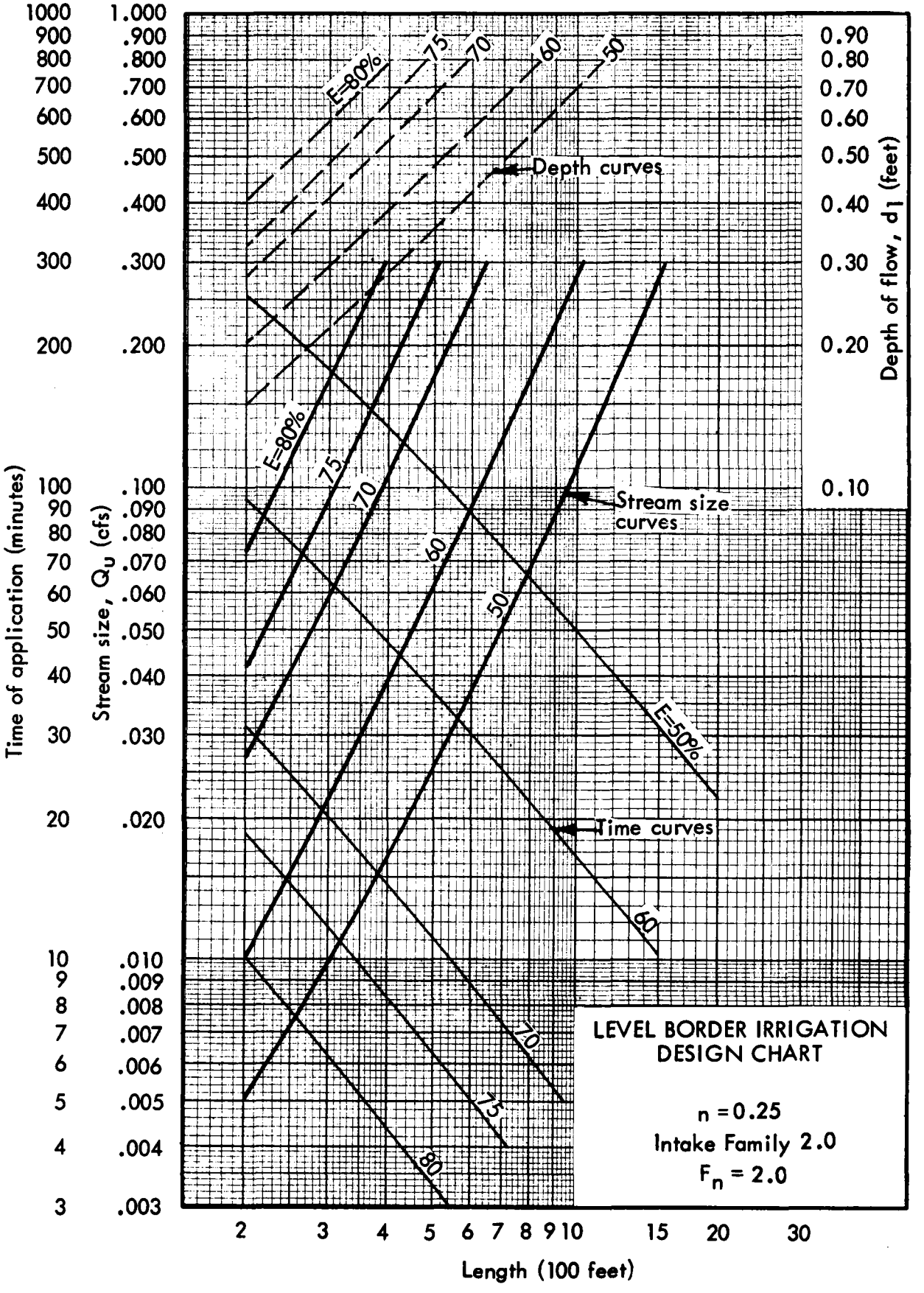

Time curves
Depth curves
Stream size curves
E=95%
E=50%
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 5.0

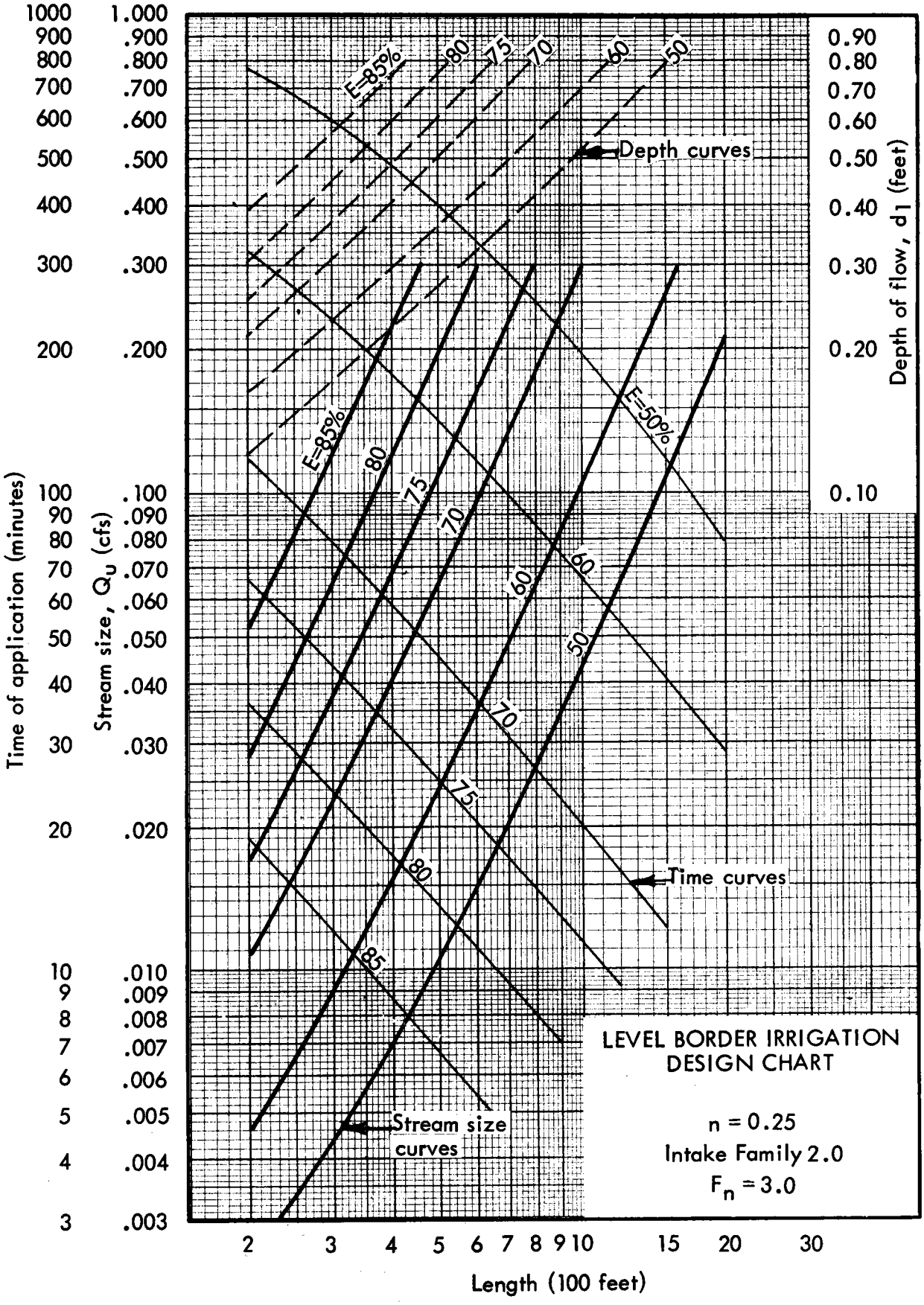

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
80
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 2.0

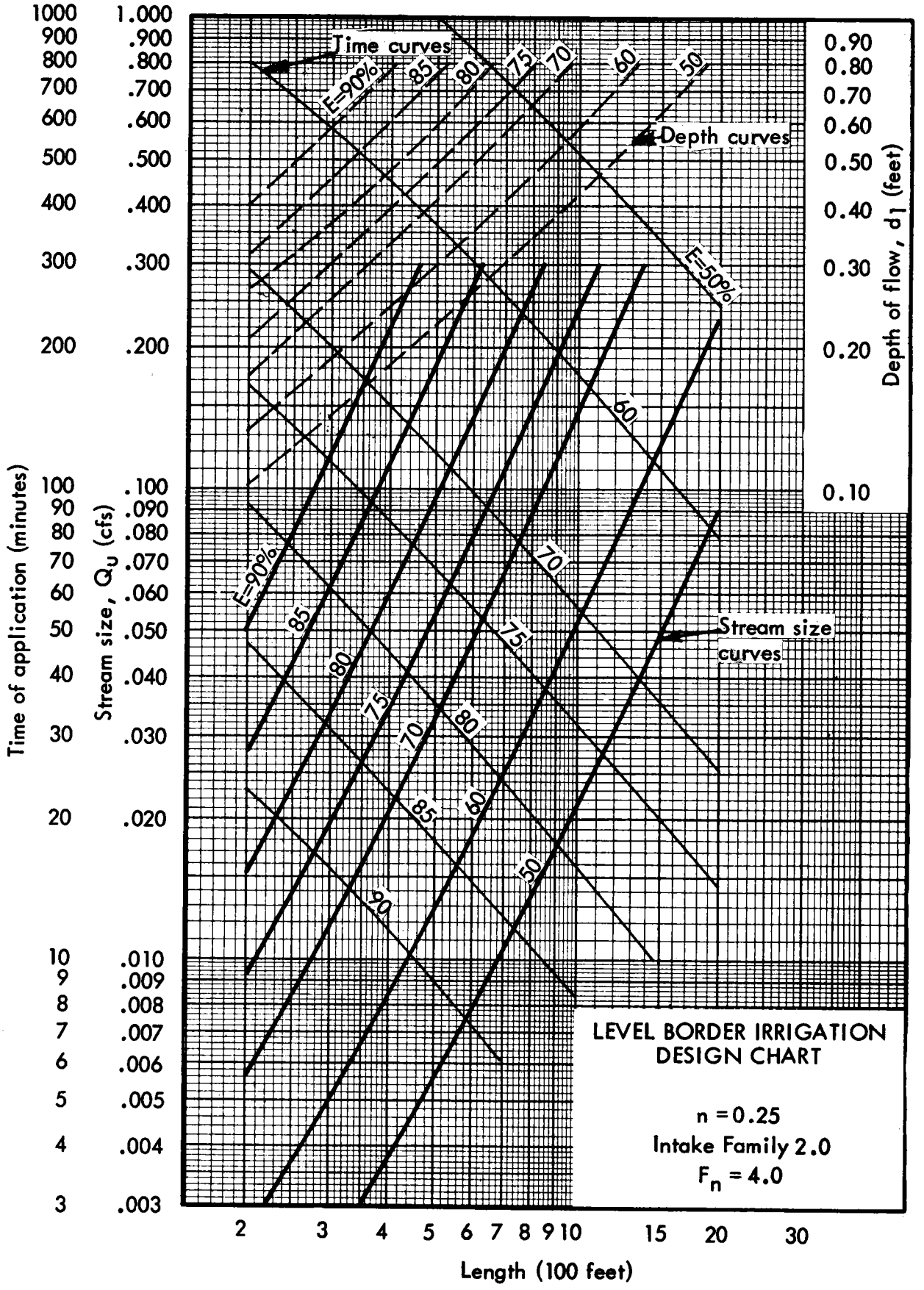

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=20%
E=90%
E=50%
85
80
75
70
60
50
60
70
75
80
85
90
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 3.0

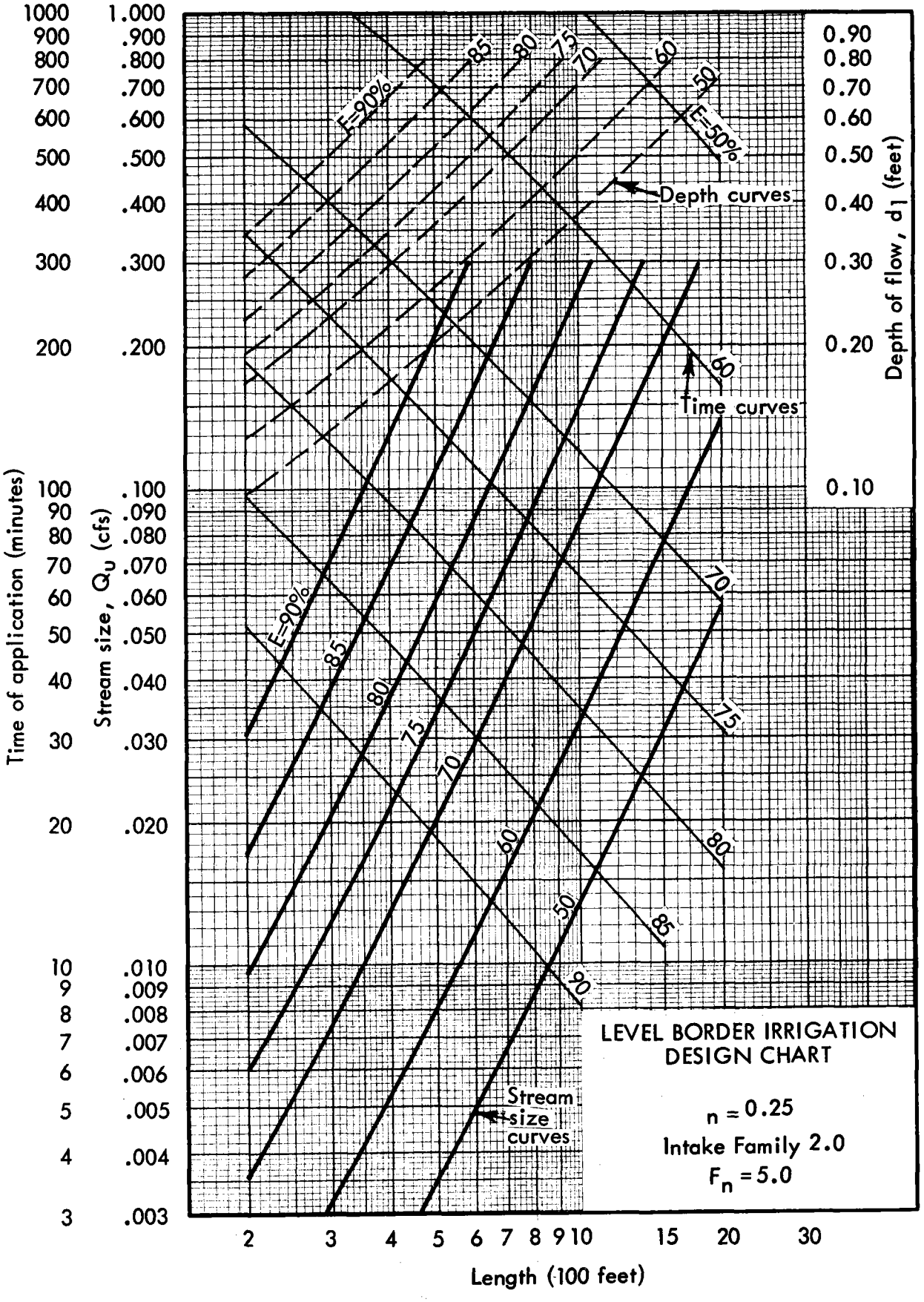

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=90%
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 4.0

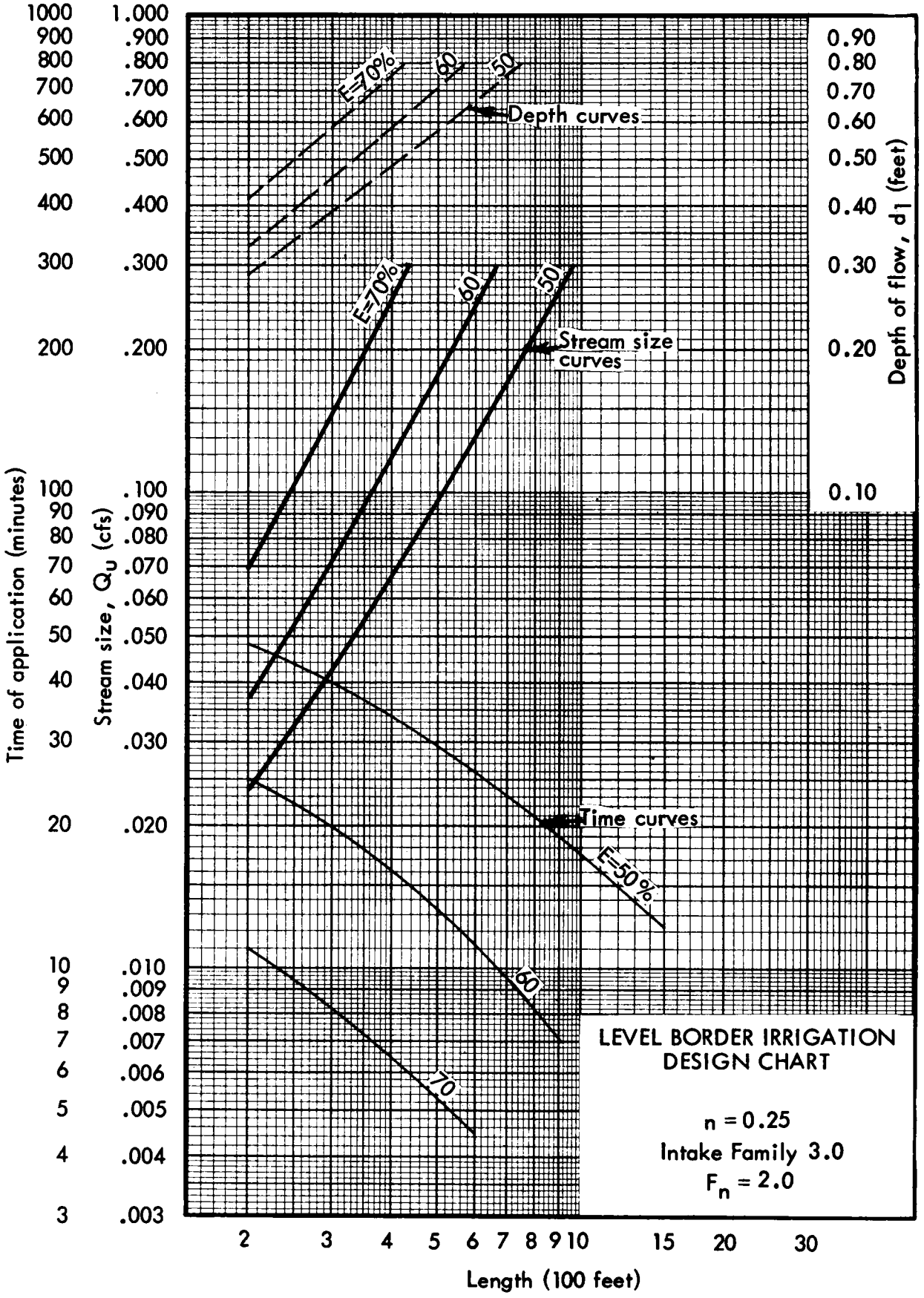

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 5.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=95%
E=50%
90
85
80
75
70
60
50

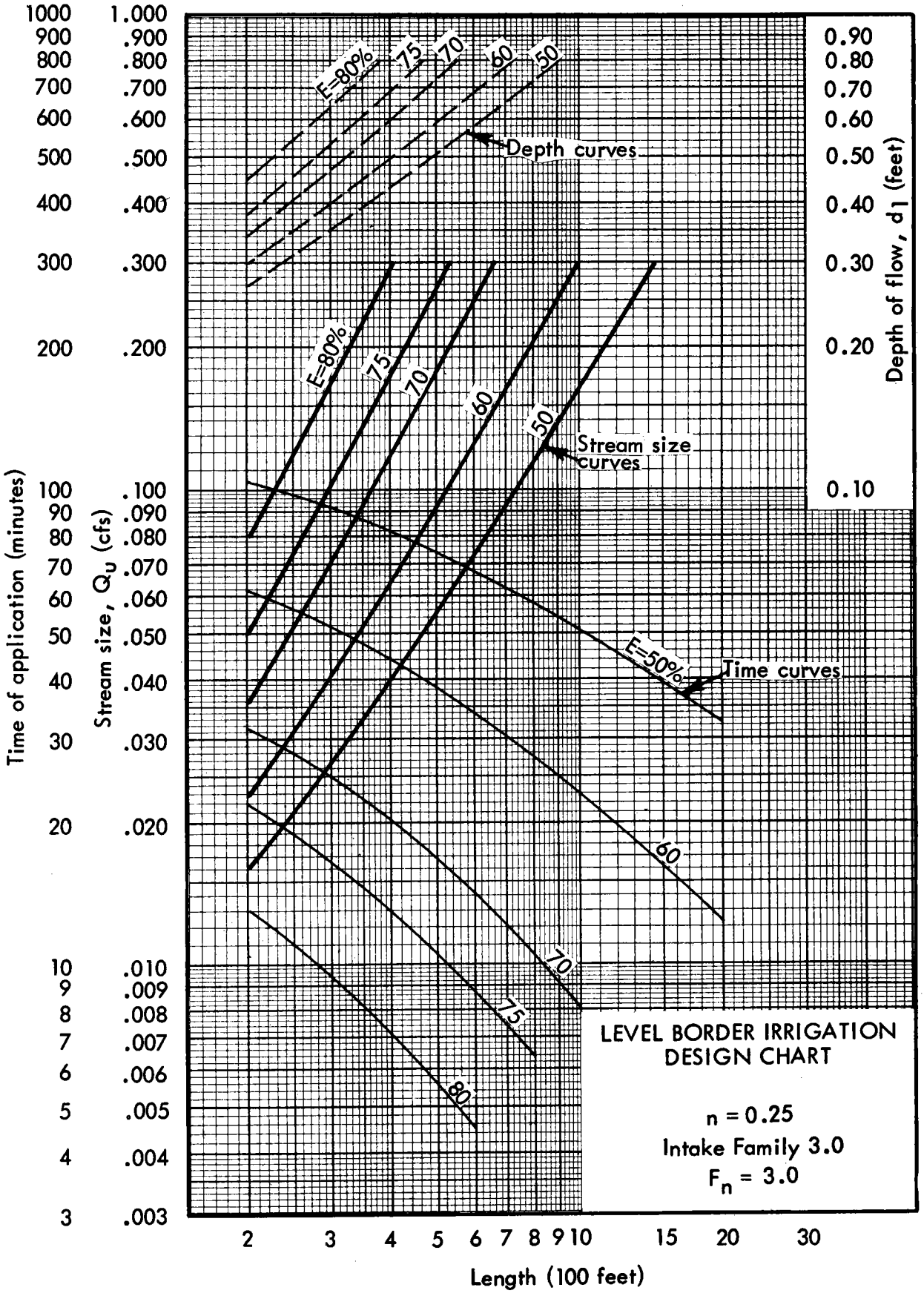

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 2.0
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
80
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 1.000
900 .900
800 .800
700 .700
600 .600
500 .500
400 .400
300 .300
200 .200
100 .100
90 .090
80 .080
70 .070
60 .060
50 .050
40 .040
30 .030
20 .020
10 .010
9 .009
8 .008
7 .007
6 .006
5 .005
4 .004
3 .003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2 3 4 5 6 7 8 9 10 15 20 30

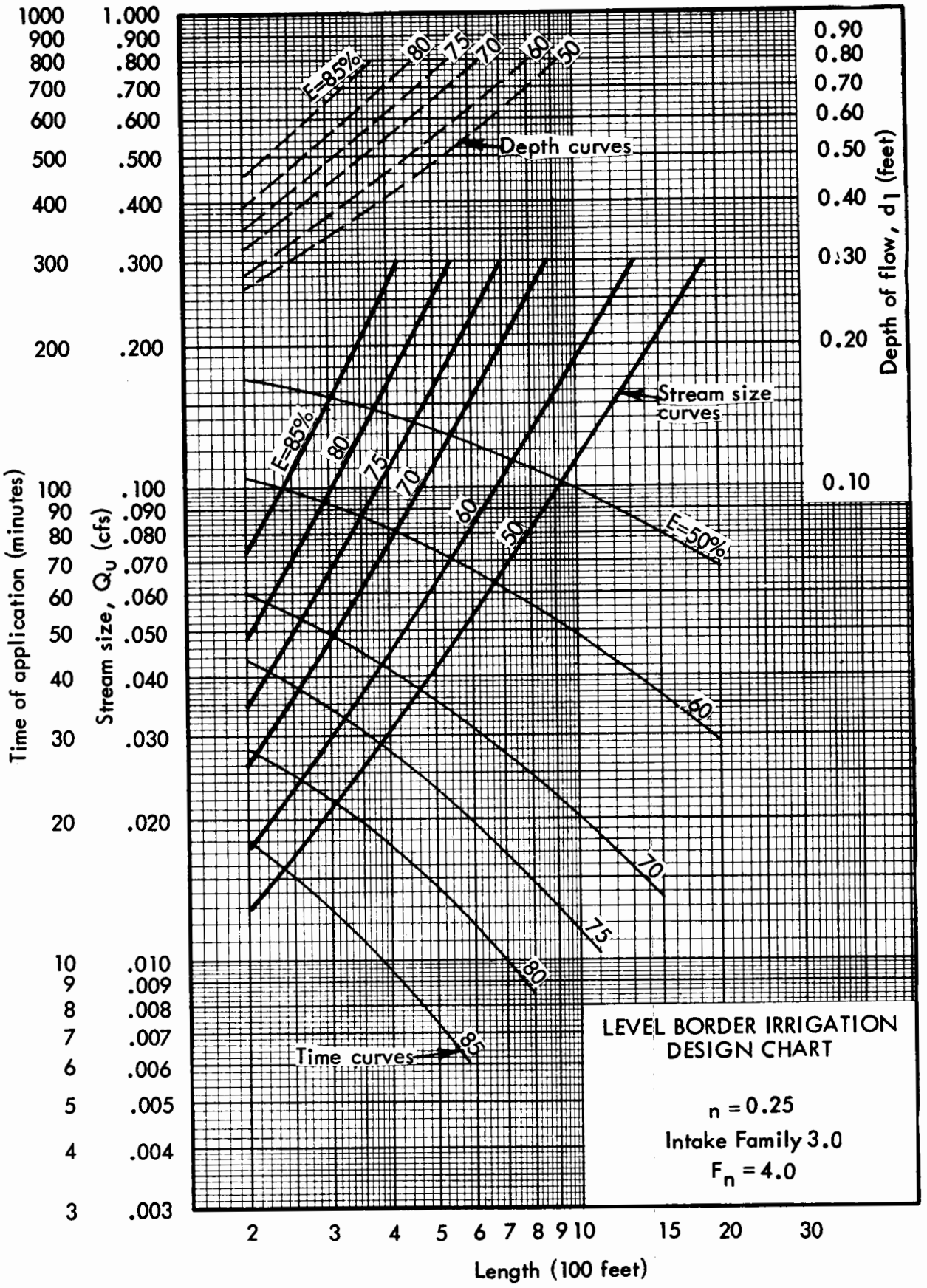

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=85%
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 3.0

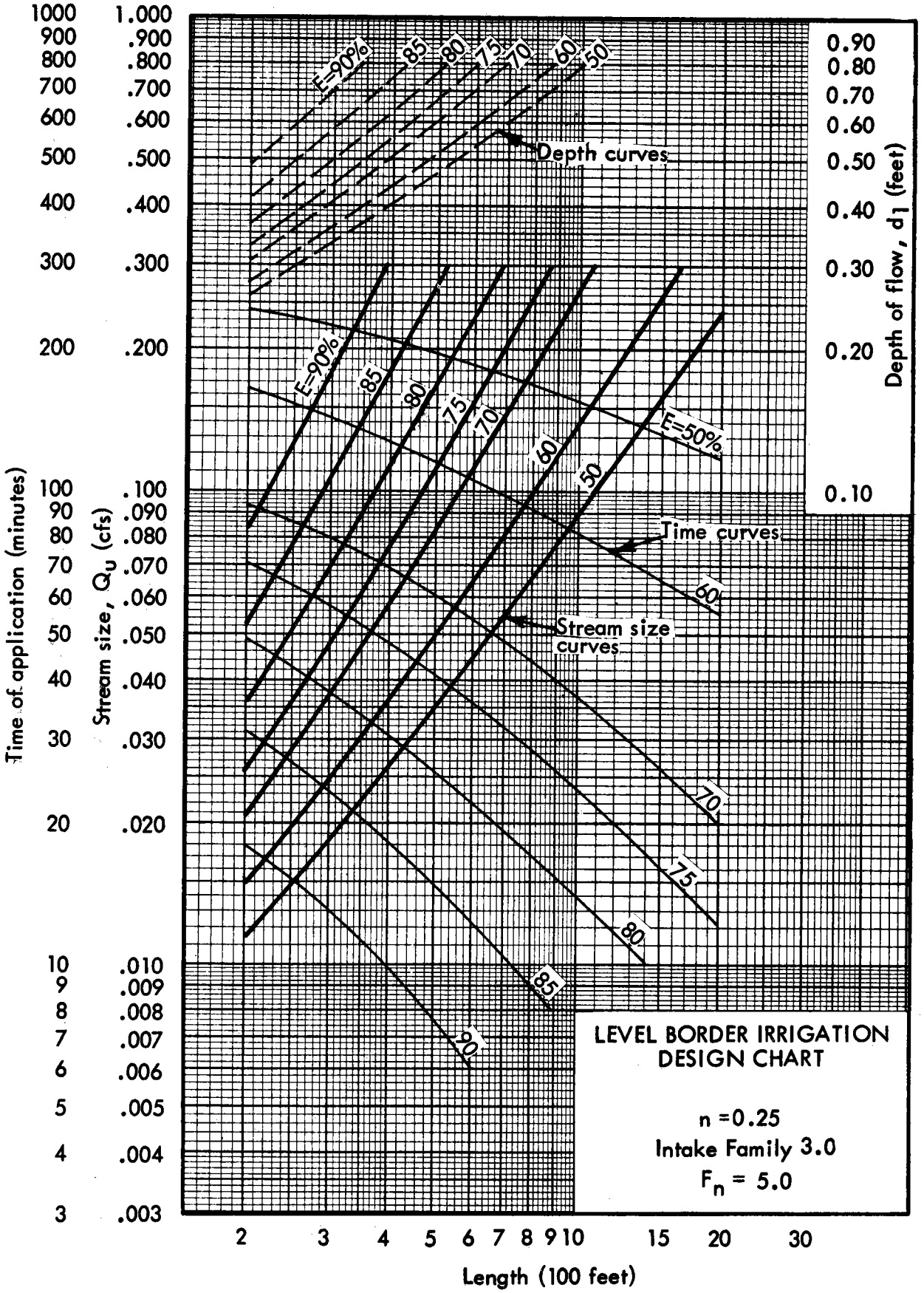

Time curves
E=90%
85
80
75
70
60
50
Depth curves
E=50%
60
70
75
80
85
90
E=90%
85
80
75
70
60
50
Stream size curves
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 4.0

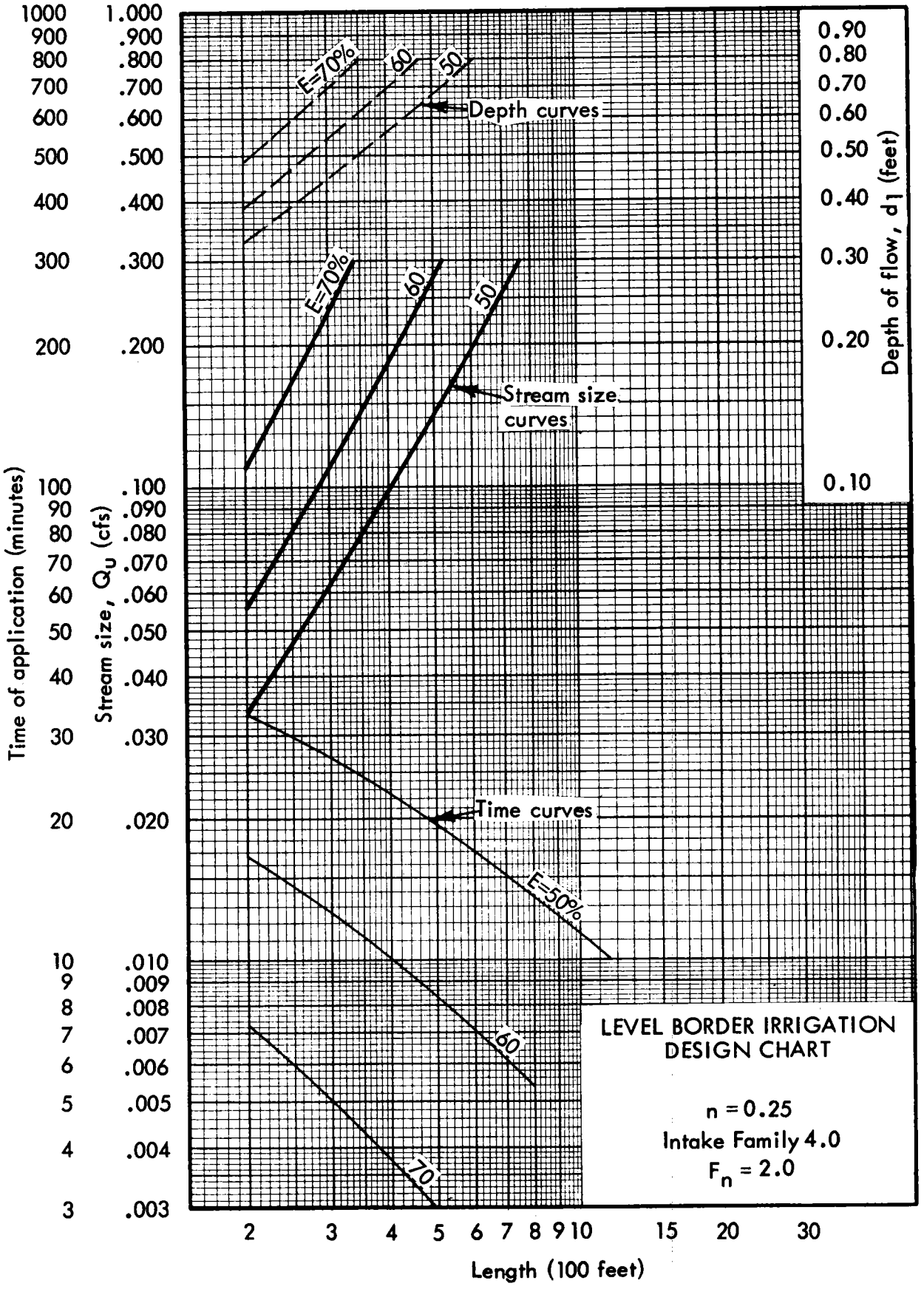

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 5.0
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
E=50%
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2
3
4
5
6
7
8
9
10
15
20
30

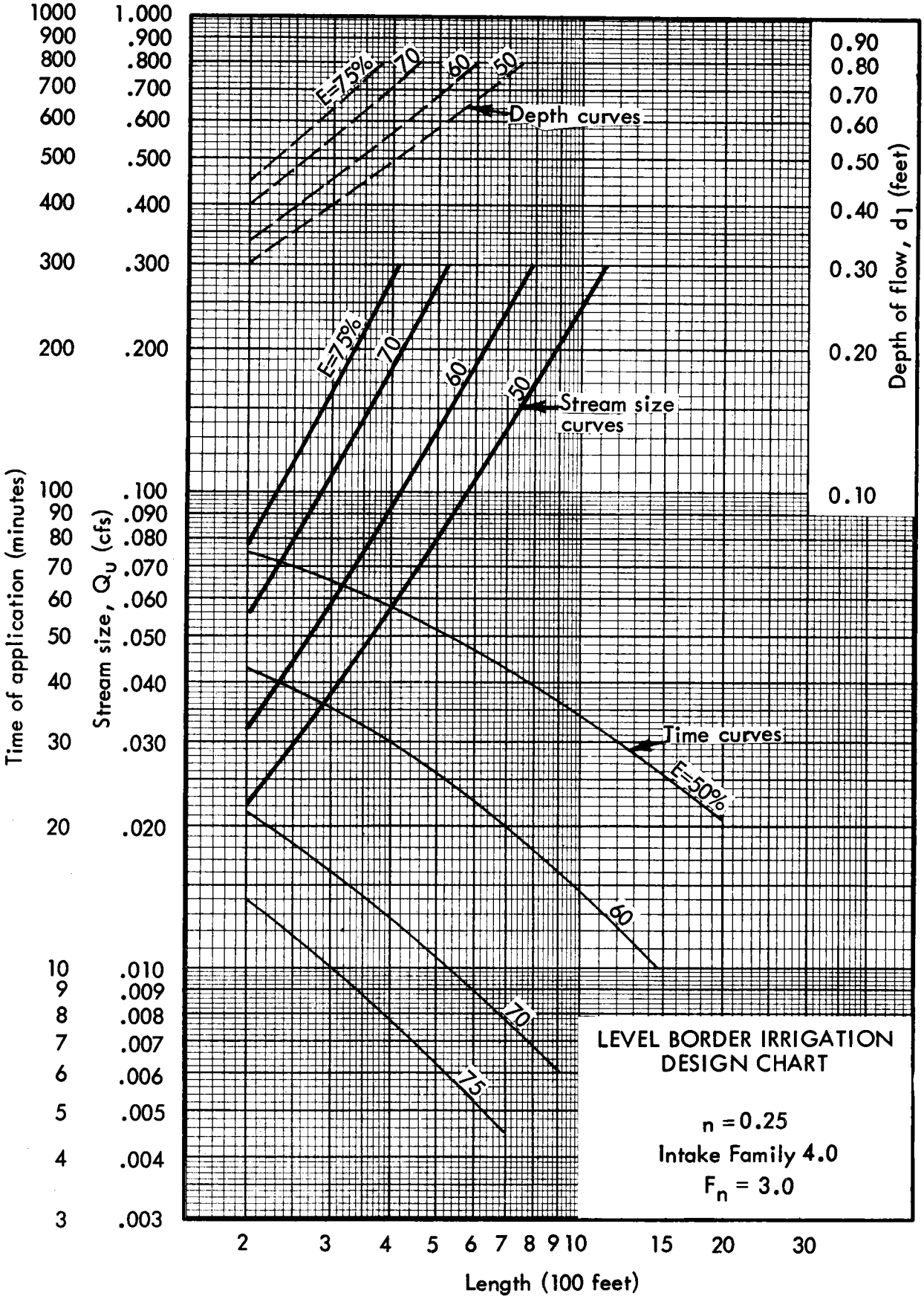

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=70%
60
50
E=50%
70
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 2.0

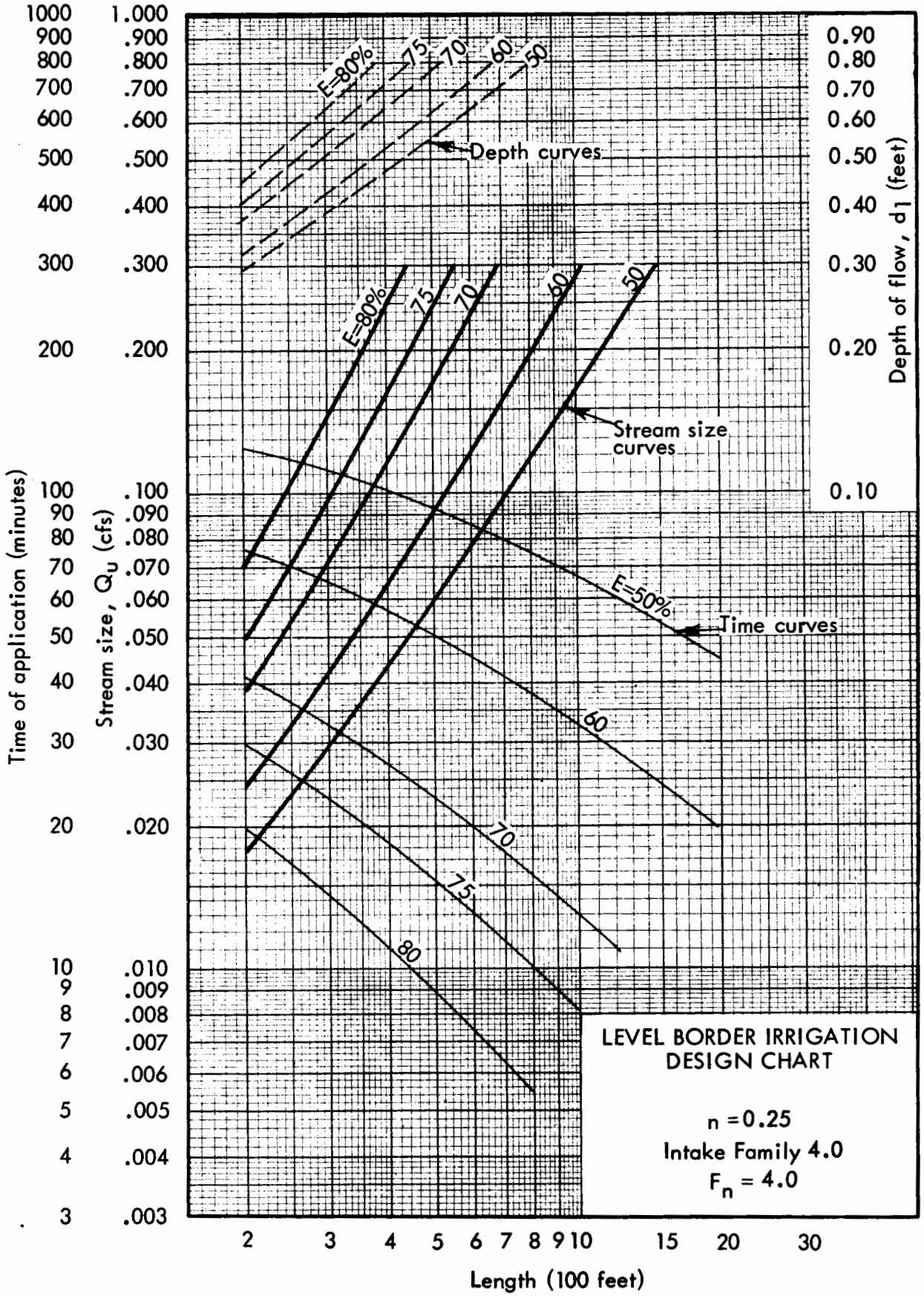

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 3.0

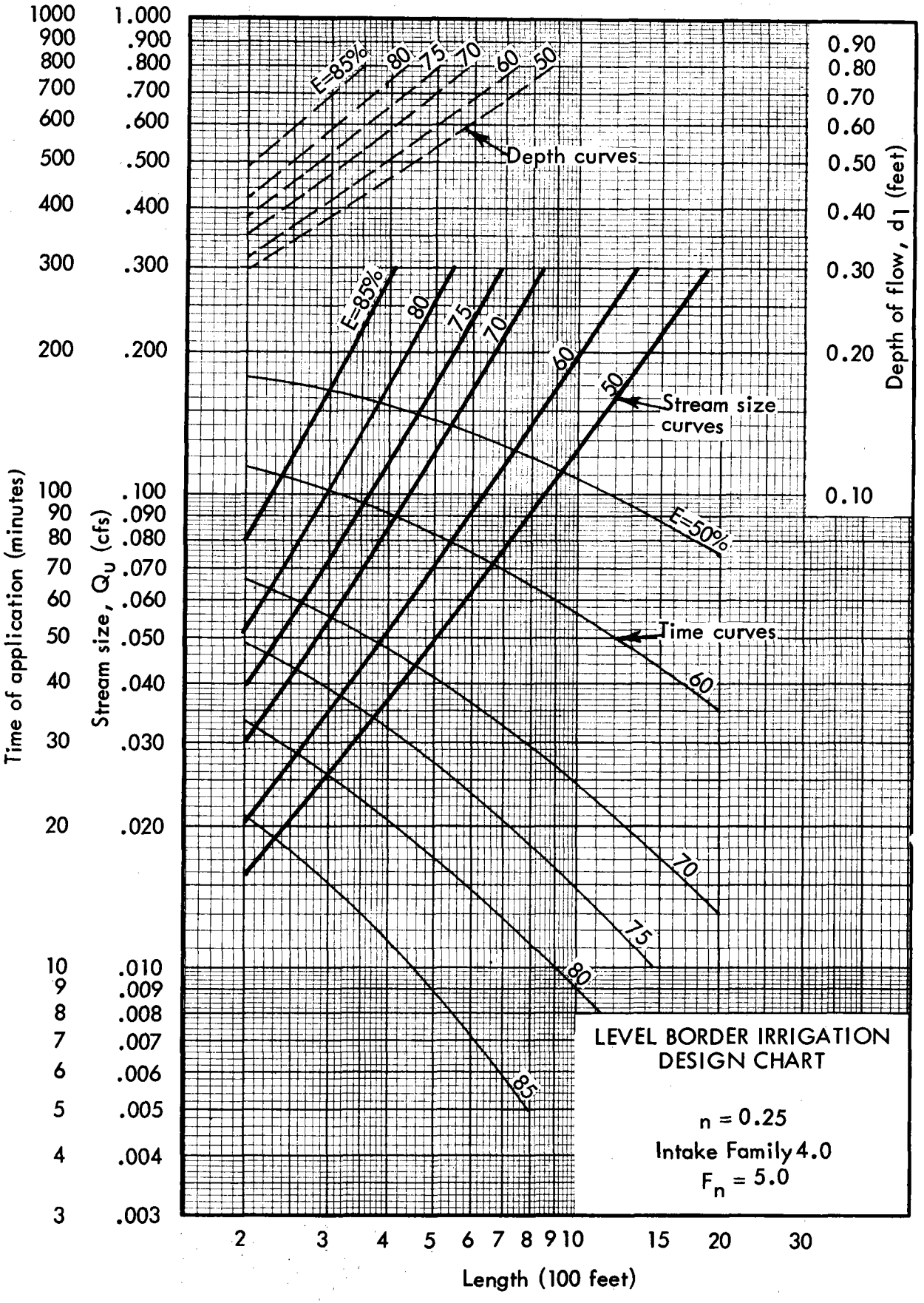

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 4.0
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
E=50%
85
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 1.000
900 .900
800 .800
700 .700
600 .600
500 .500
400 .400
300 .300
200 .200
100 .100
90 .090
80 .080
70 .070
60 .060
50 .050
40 .040
30 .030
20 .020
10 .010
9 .009
8 .008
7 .007
6 .006
5 .005
4 .004
3 .003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2 3 4 5 6 7 8 9 10 15 20 30

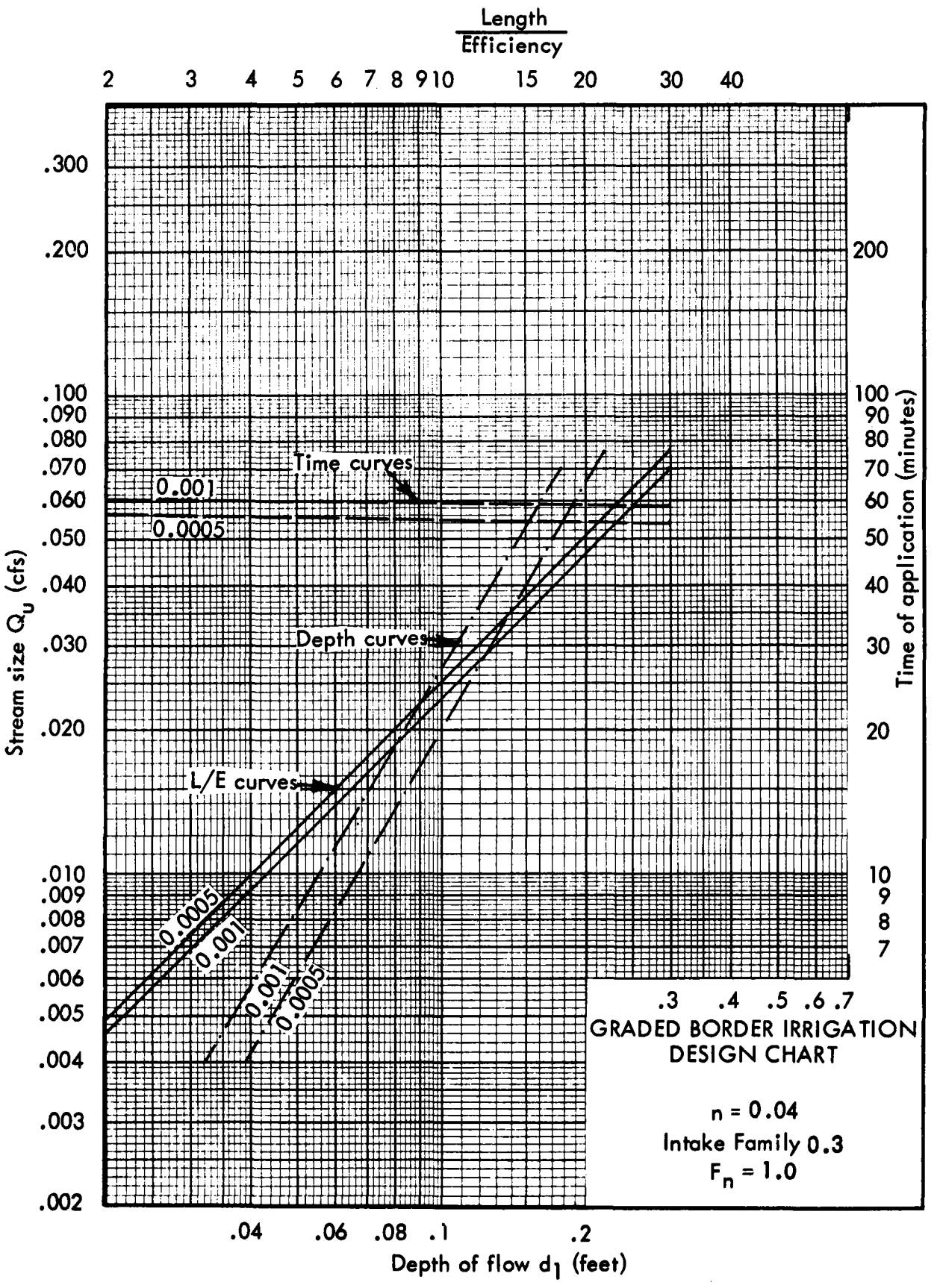

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Time curves
Stream size curves
E=90%
85
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n =0.25
Intake Family 3.0
F_n = 5.0

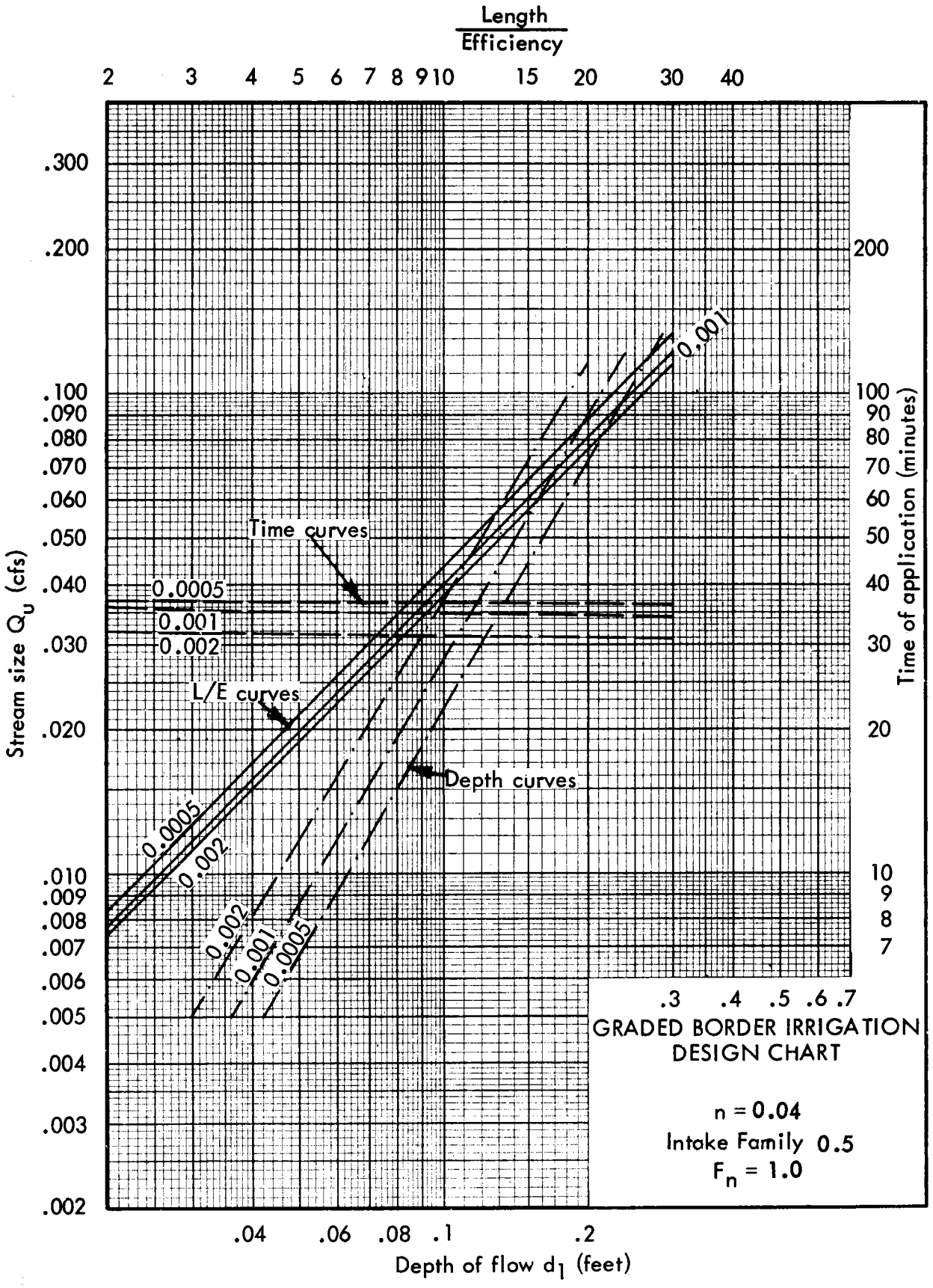

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 4.0
F_n = 2.0
Depth curves
Stream size curves
Time curves
E=70%
60
50
E=50%
70
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 900 800 700 600 500 400 300 200 100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3
1.000 .900 .800 .700 .600 .500 .400 .300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003
0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10
2 3 4 5 6 7 8 9 10 15 20 30

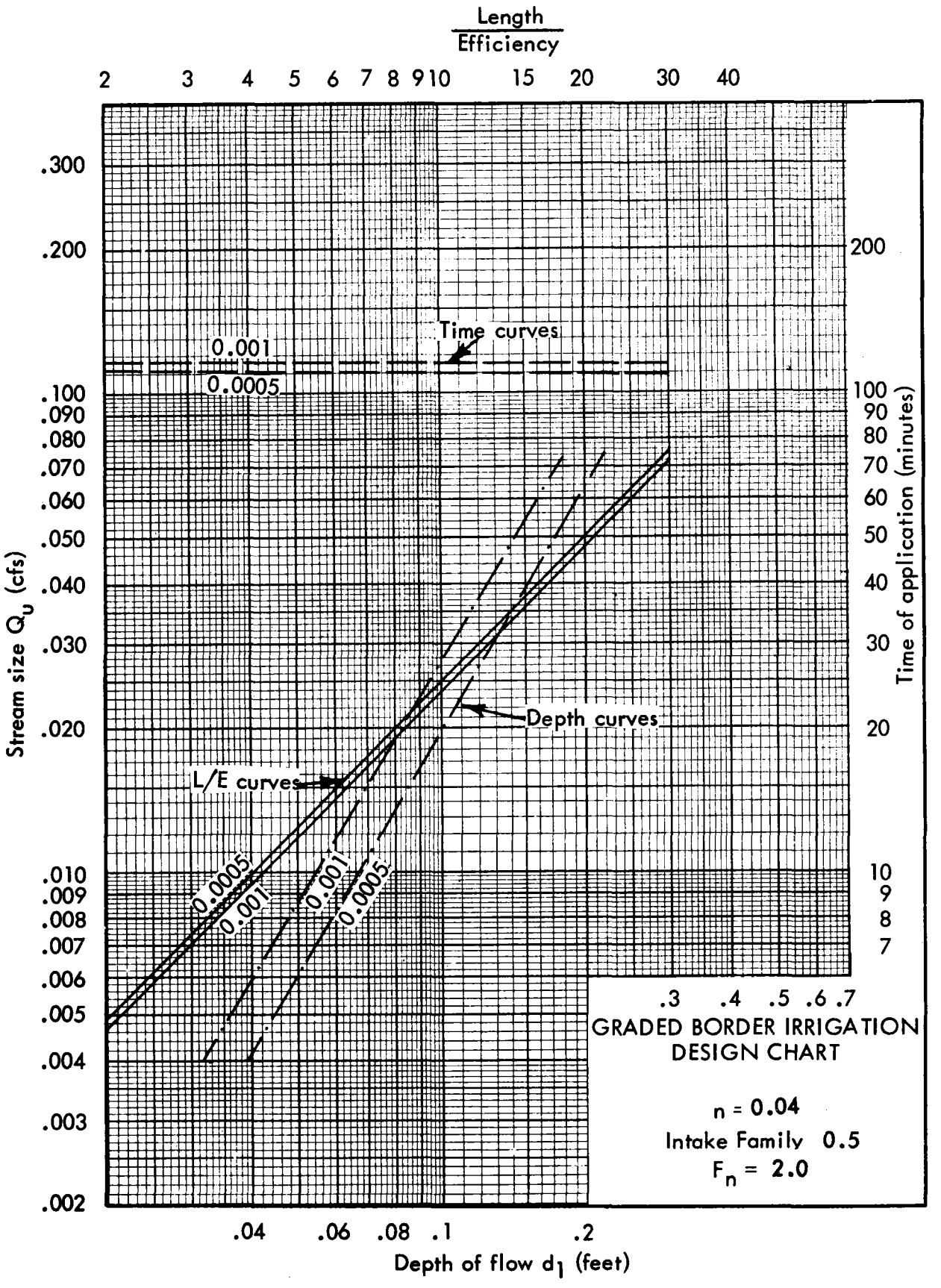

LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 4.0
F_n = 3.0
Depth curves
E=75%
70
60
50
Stream size curves
Time curves
E=50%
60
70
75
Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
1000 1.000
900 .900
800 .800
700 .700
600 .600
500 .500
400 .400
300 .300
200 .200
100 .100
90 .090
80 .080
70 .070
60 .060
50 .050
40 .040
30 .030
20 .020
10 .010
9 .009
8 .008
7 .007
6 .006
5 .005
4 .004
3 .003
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
2 3 4 5 6 7 8 9 10 15 20 30

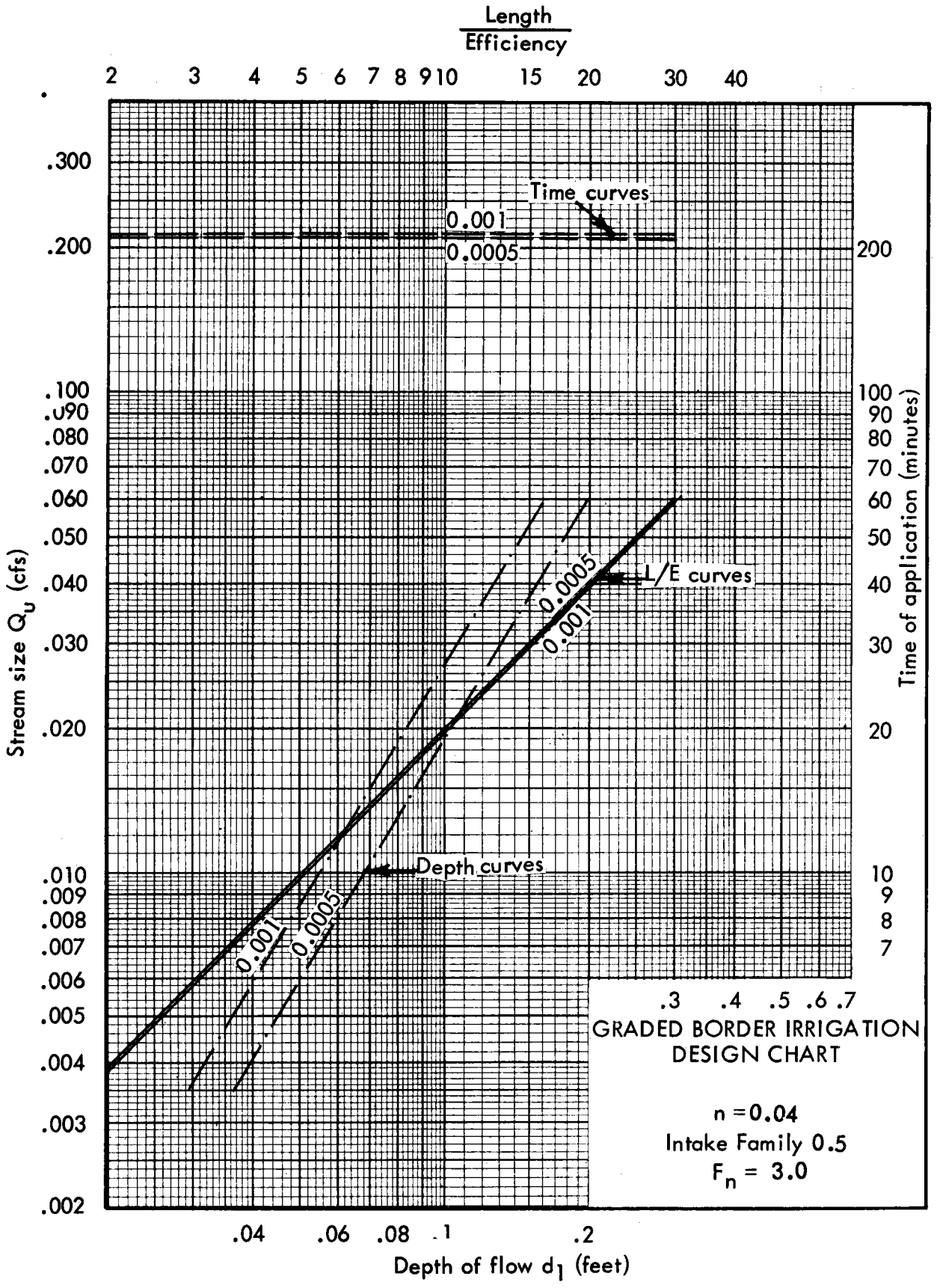

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=80%
75
70
60
50
E=50%
80
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 4.0
F_n = 4.0

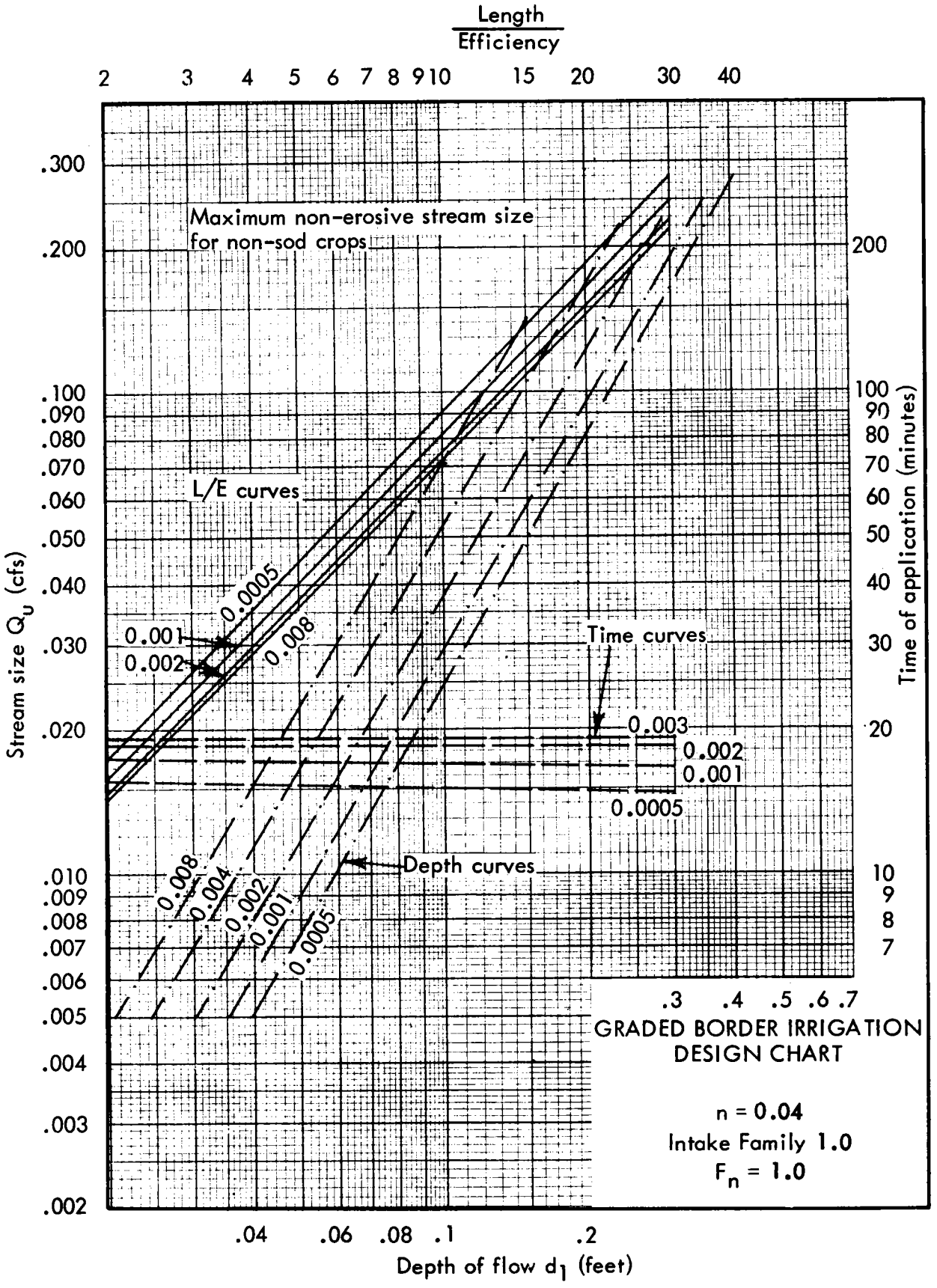

Time of application (minutes)
Stream size, Q_u (cfs)
Depth of flow, d_1 (feet)
Length (100 feet)
Depth curves
Stream size curves
Time curves
E=85%
80
75
70
60
50
E=50%
LEVEL BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 4.0
F_n = 5.0

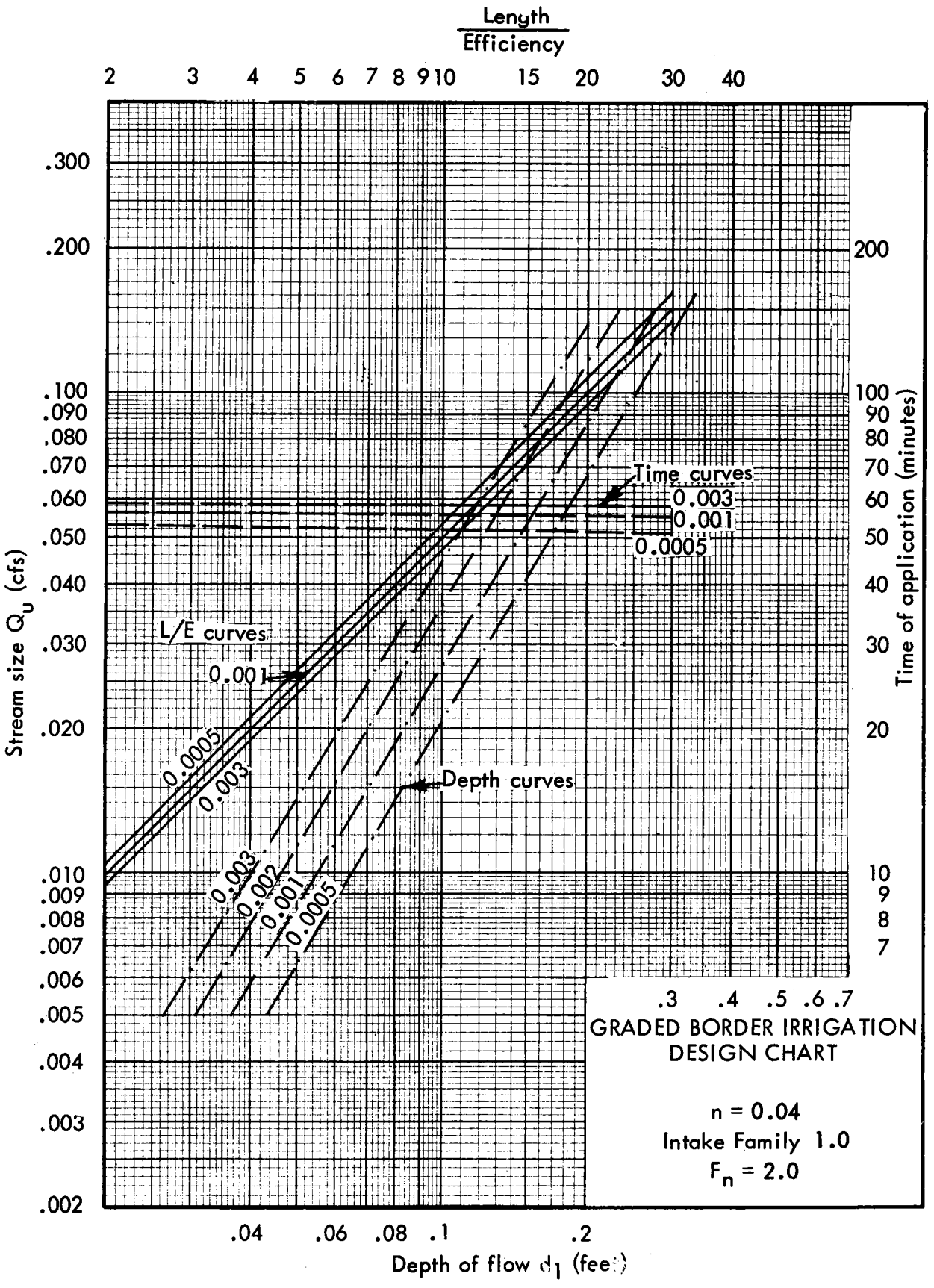

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
Time curves
0.001
0.0005
Depth curves
L/E curves
0.0005
0.001
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 0.3
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

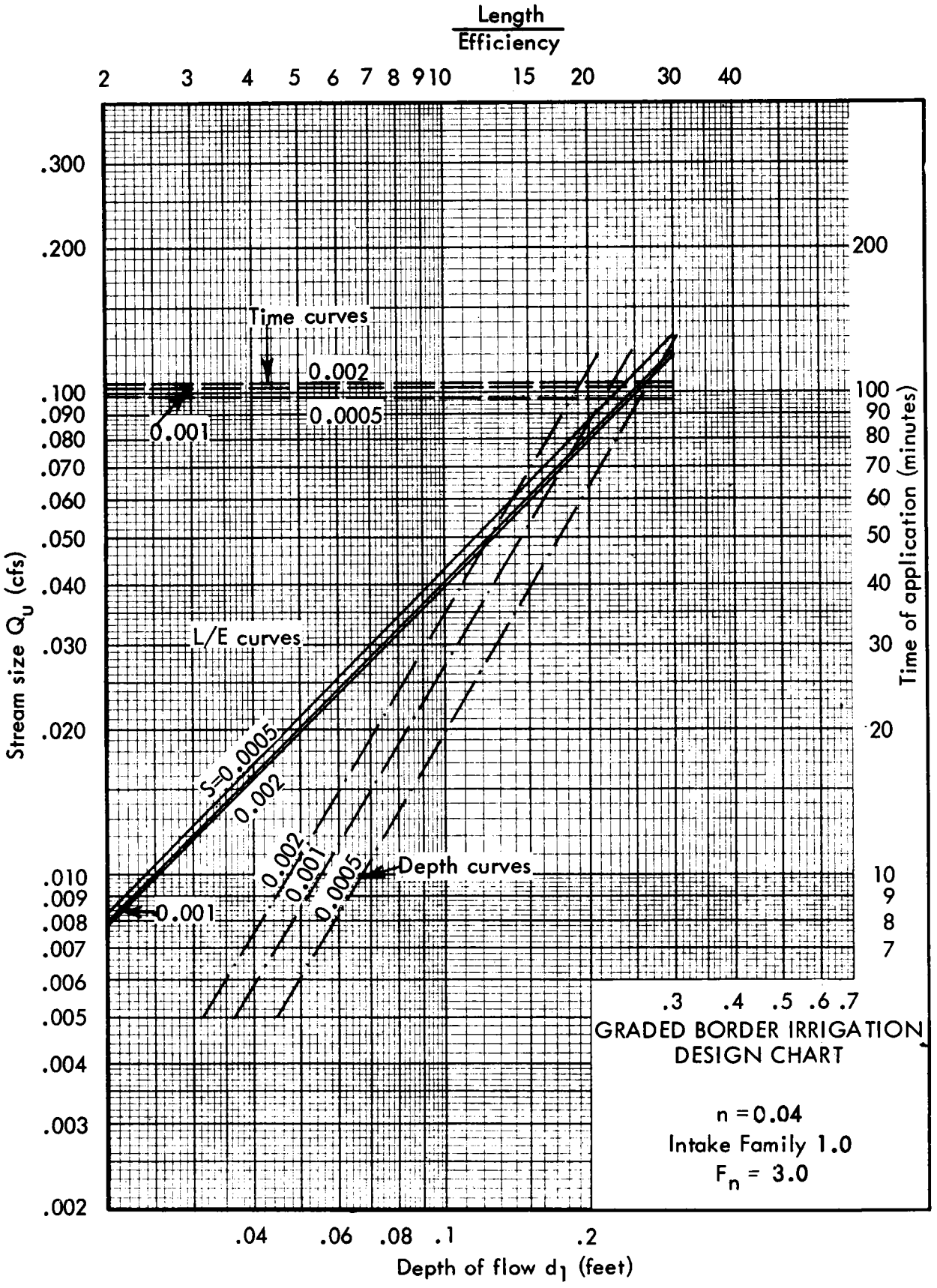

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
Time curves
L/E curves
Depth curves
0.0005
0.001
0.002
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 1.0

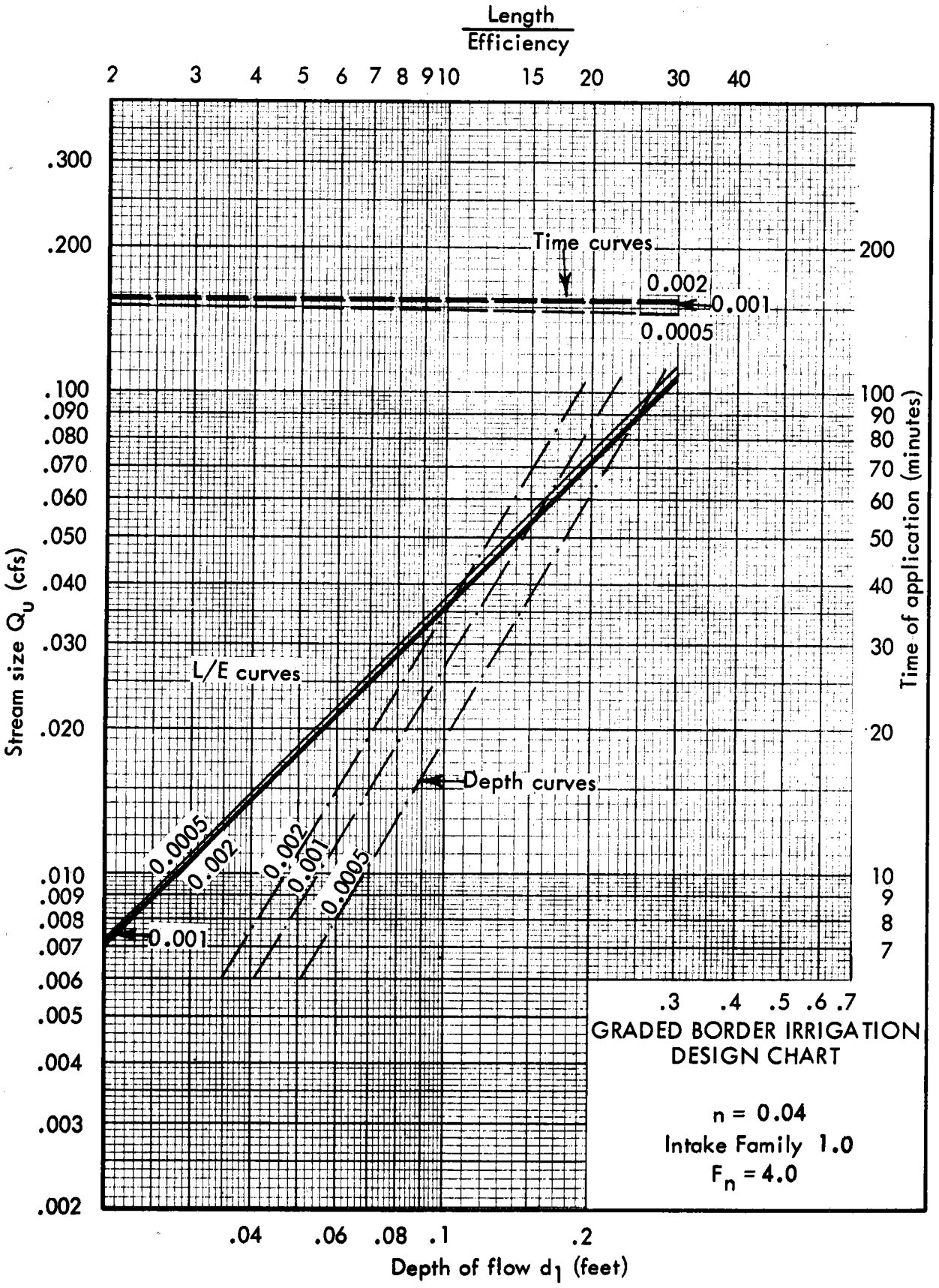

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
Time curves
0.001
0.0005
Depth curves
L/E curves
0.0005
0.001
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

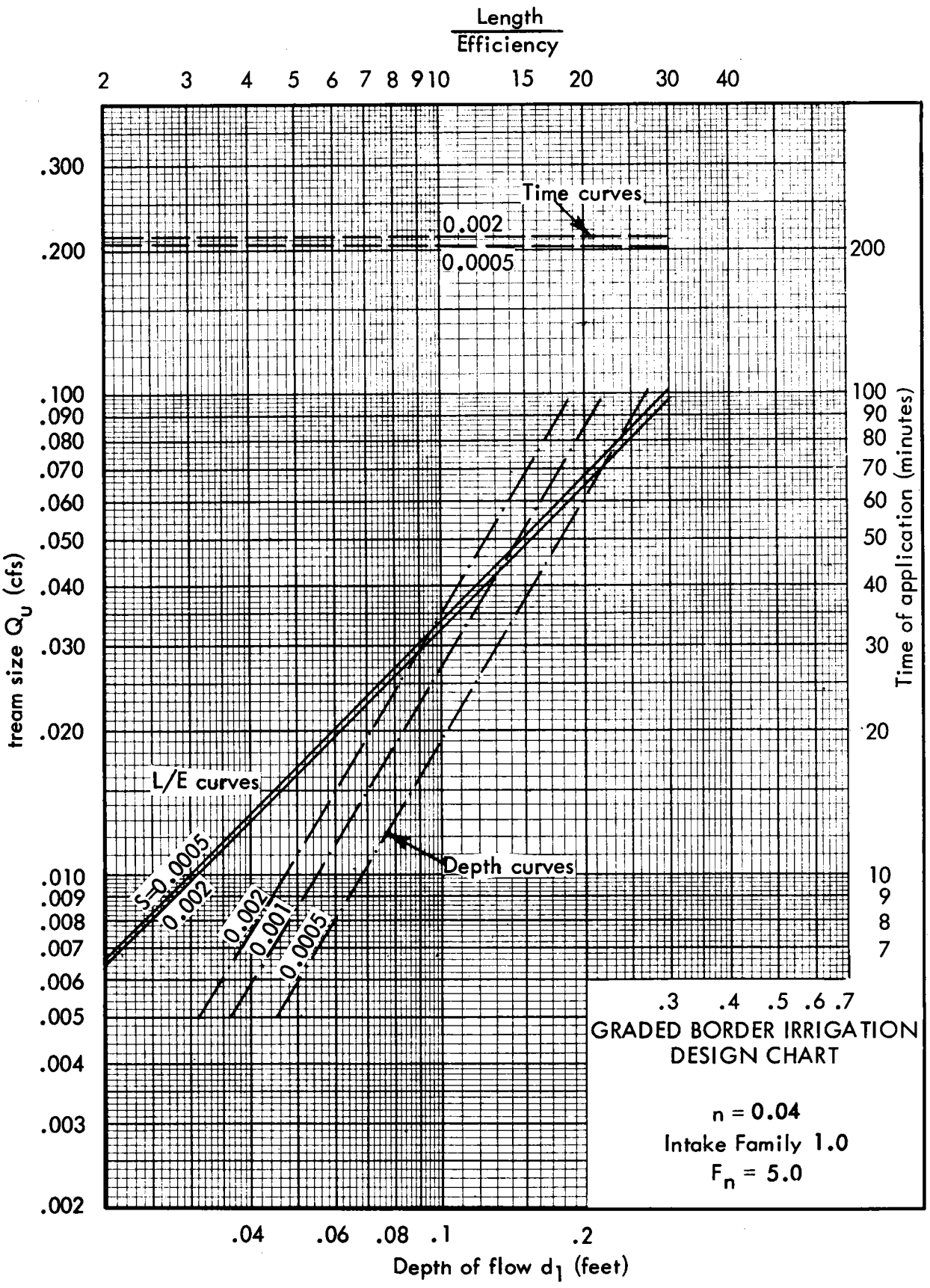

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.001
0.0005
L/E curves
0.0005
0.001
Depth curves
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 0.5
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

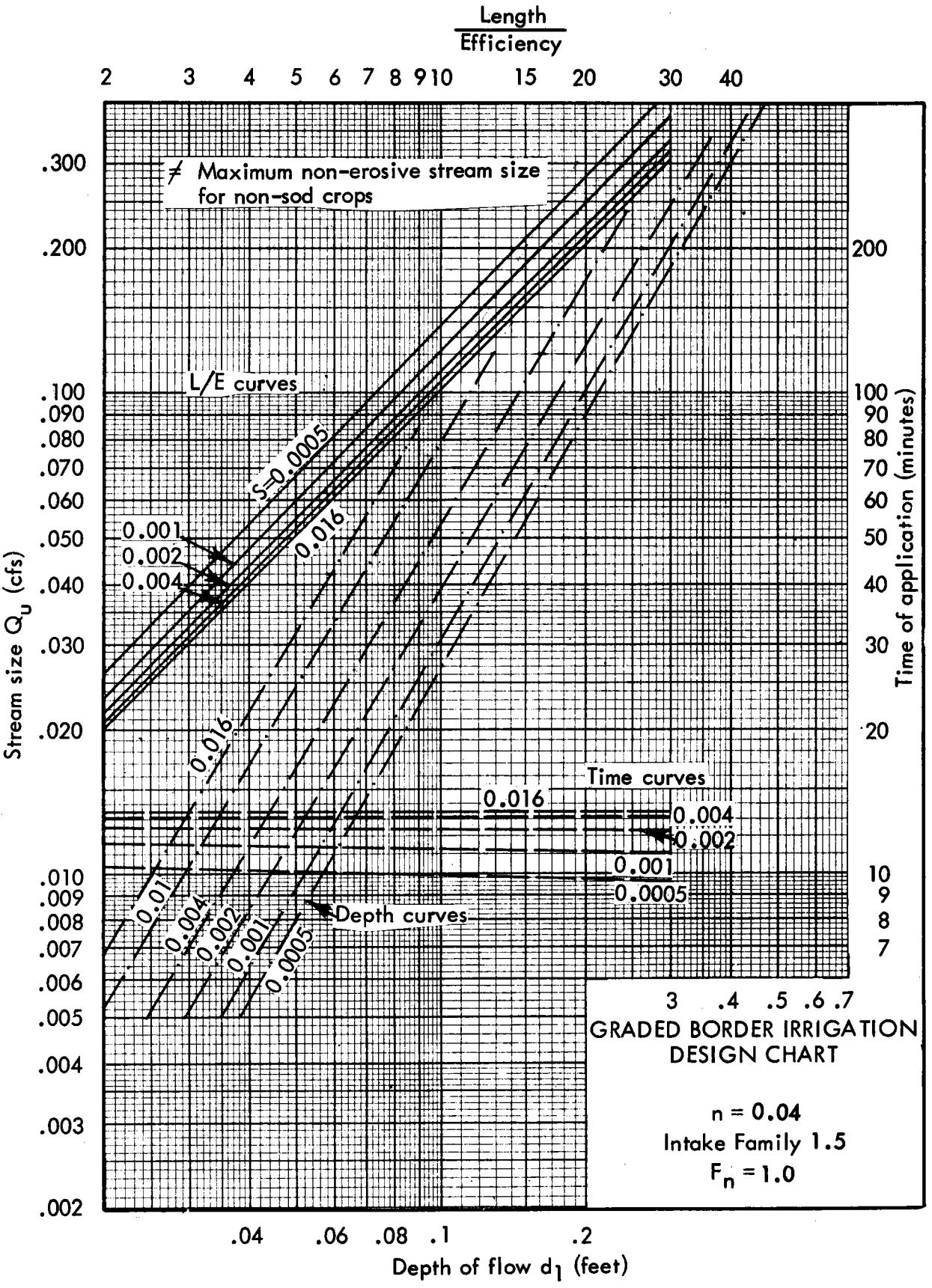

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
L/E curves
0.0005
0.001
0.002
0.008
Time curves
0.003
0.002
0.001
0.0005
Depth curves
0.008
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

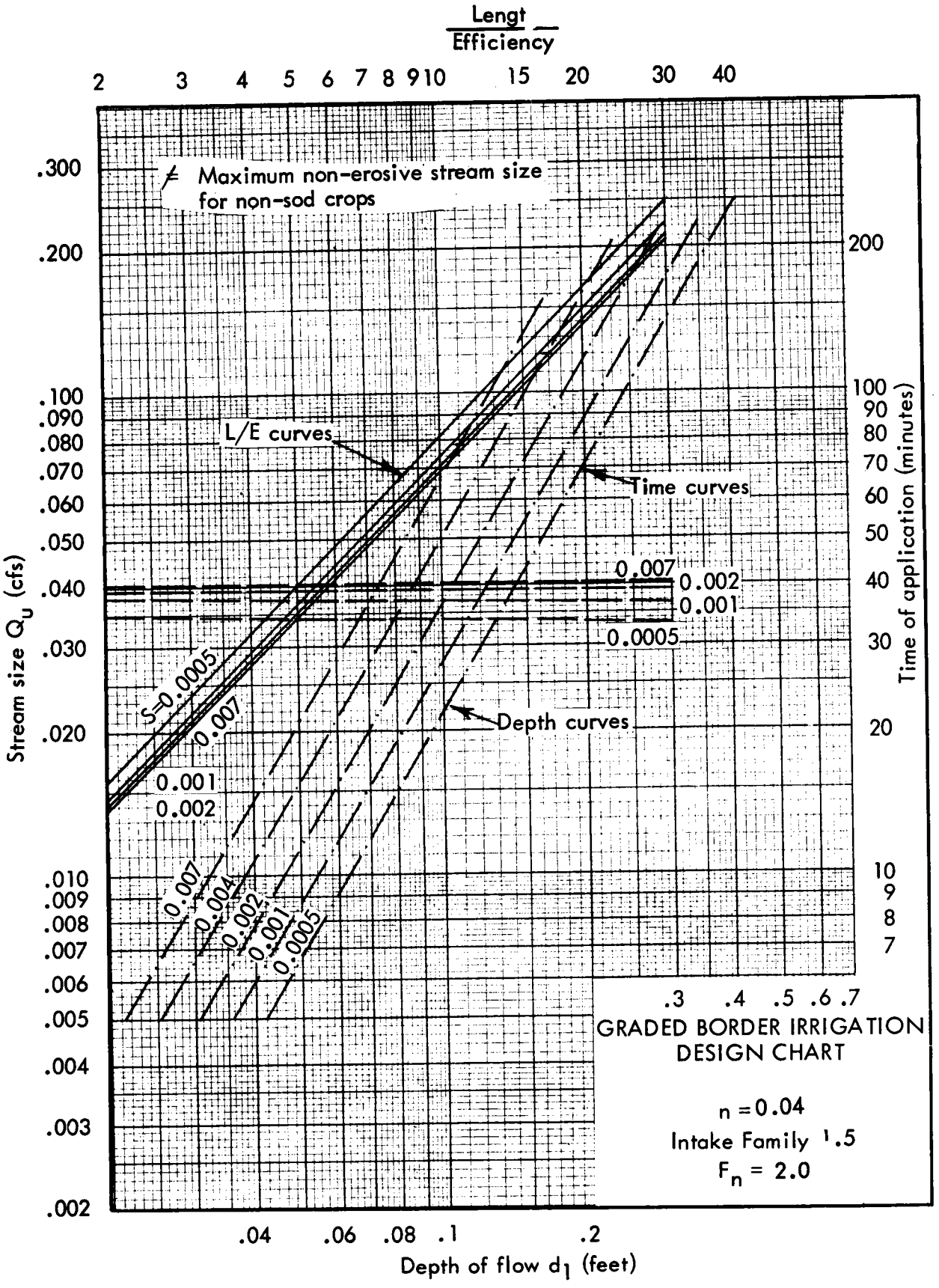

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
Time curves
0.003
0.001
0.0005
L/E curves
0.001
0.0005
0.003
Depth curves
0.003
0.002
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

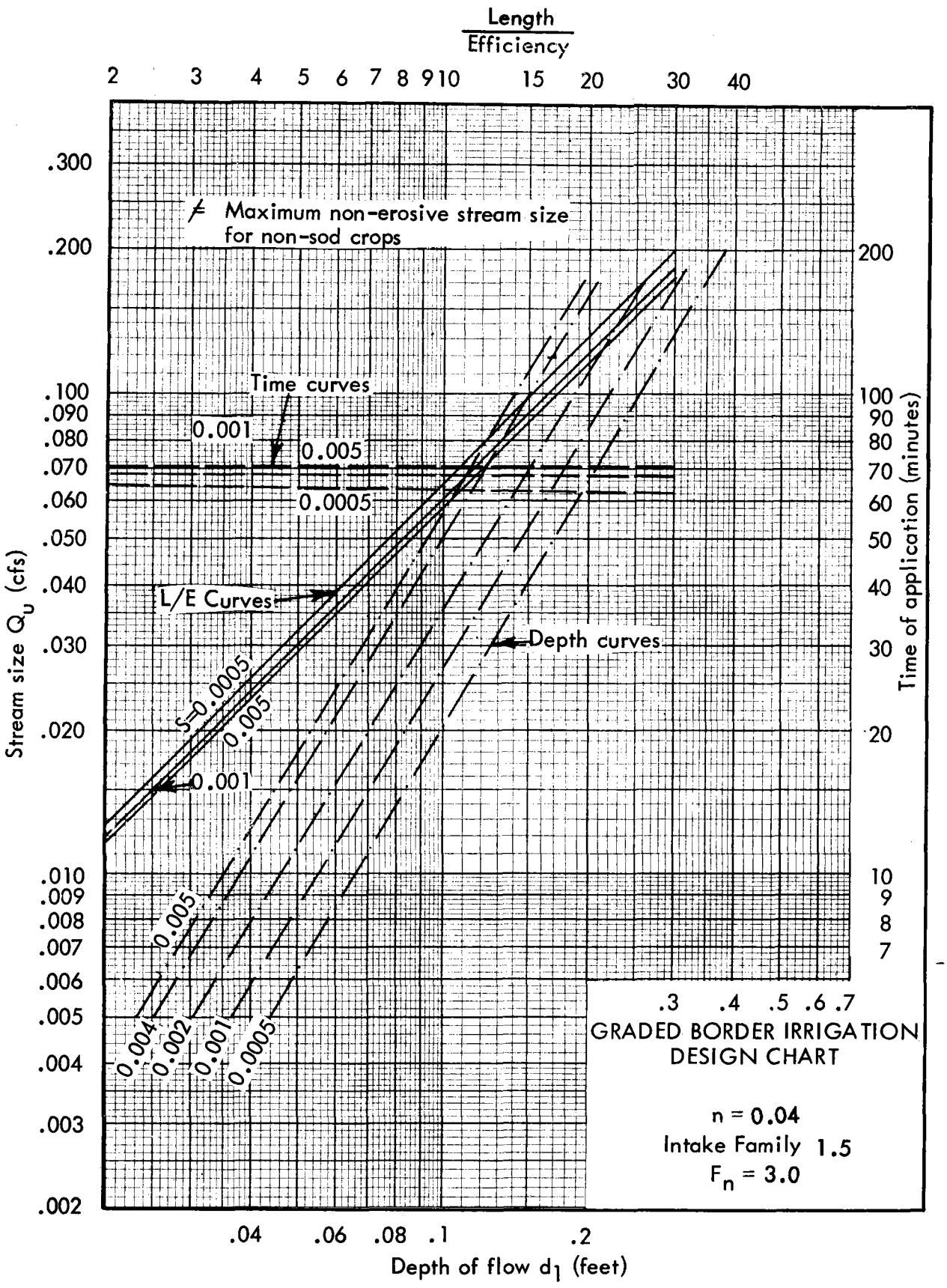

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
Time curves
0.002
0.0005
0.001
L/E curves
S=0.0005
0.002
0.002
0.001
0.0005
Depth curves
0.001
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

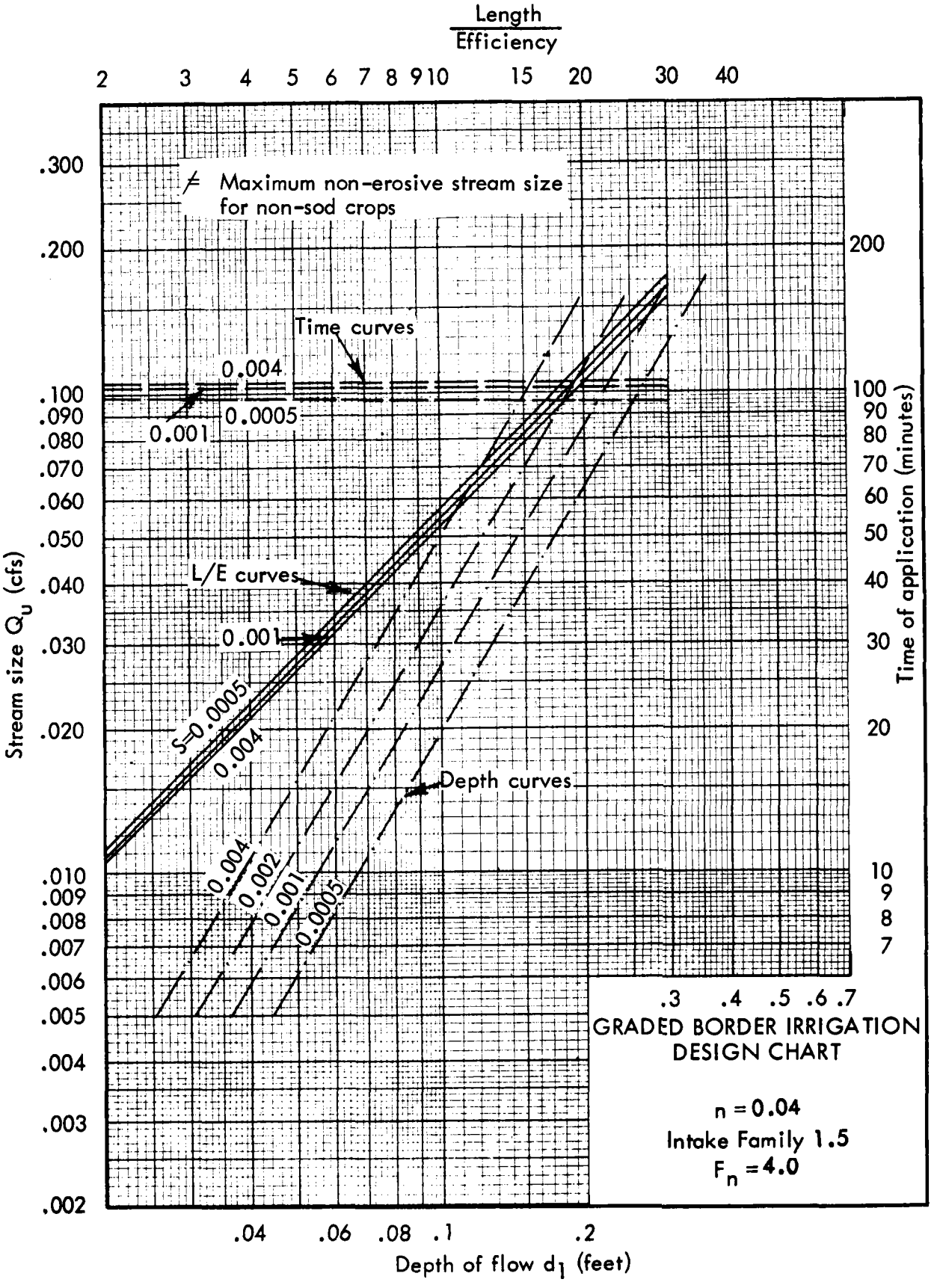

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
Time curves
0.002
0.001
0.0005
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
L/E curves
Depth curves
0.0005
0.002
0.001
0.002
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

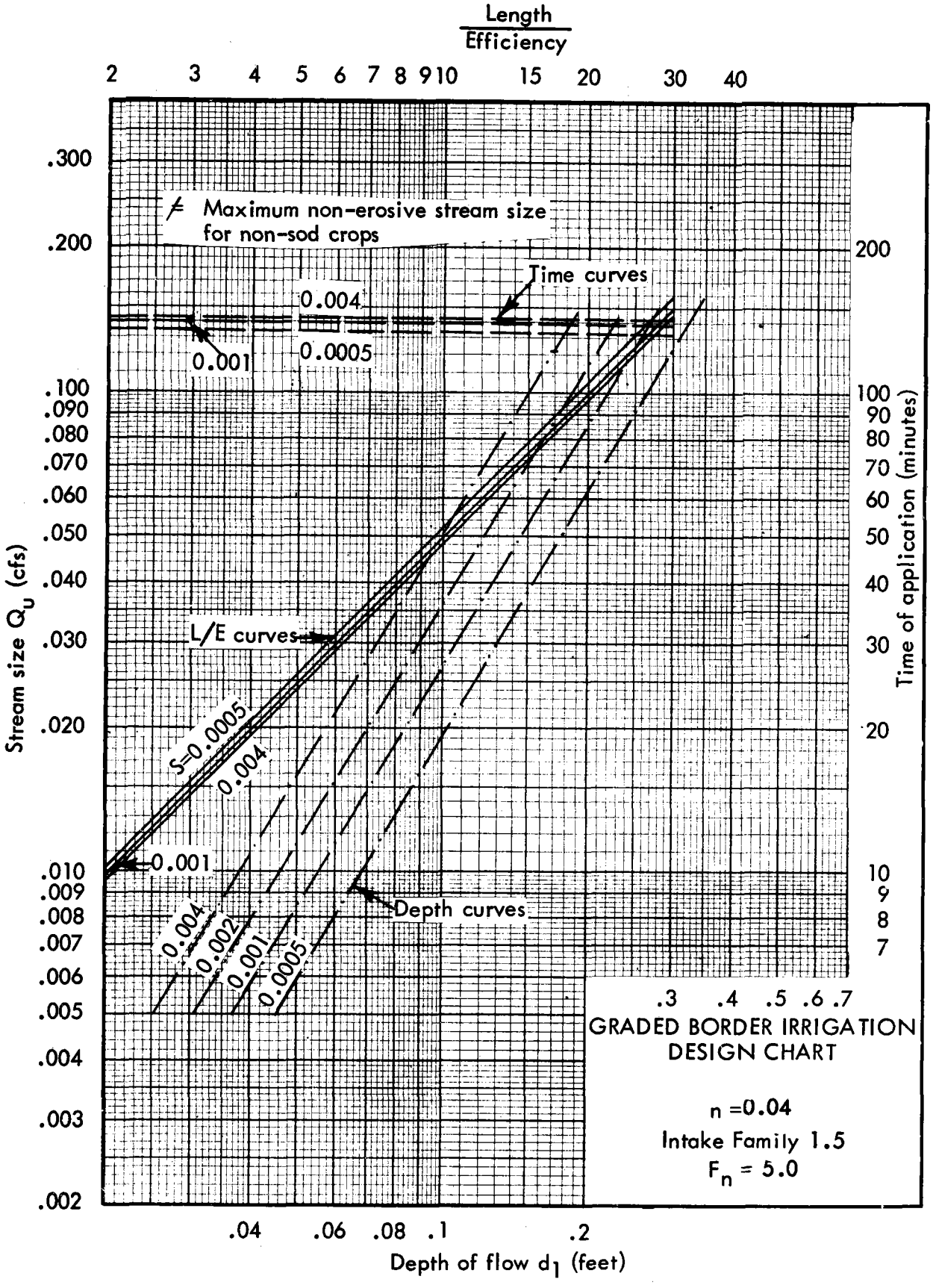

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.002
0.0005
L/E curves
S=0.0005
0.002
0.002
0.001
0.0005
Depth curves
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
tream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

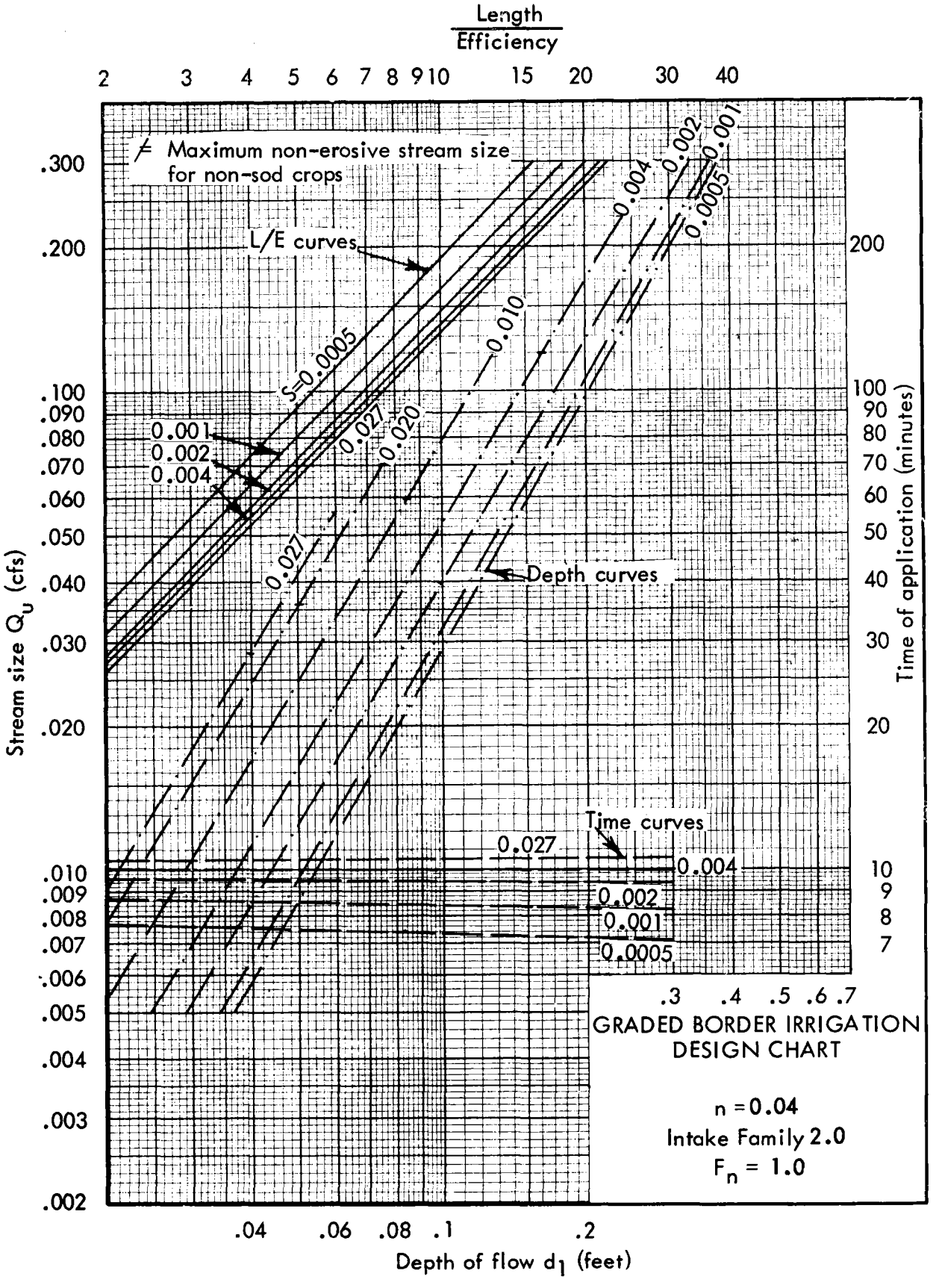

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
S=0.0005
0.001
0.002
0.004
0.016
0.016
0.016
Time curves
0.004
0.002
0.001
0.0005
0.01
0.004
0.002
0.001
0.0005
Depth curves
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

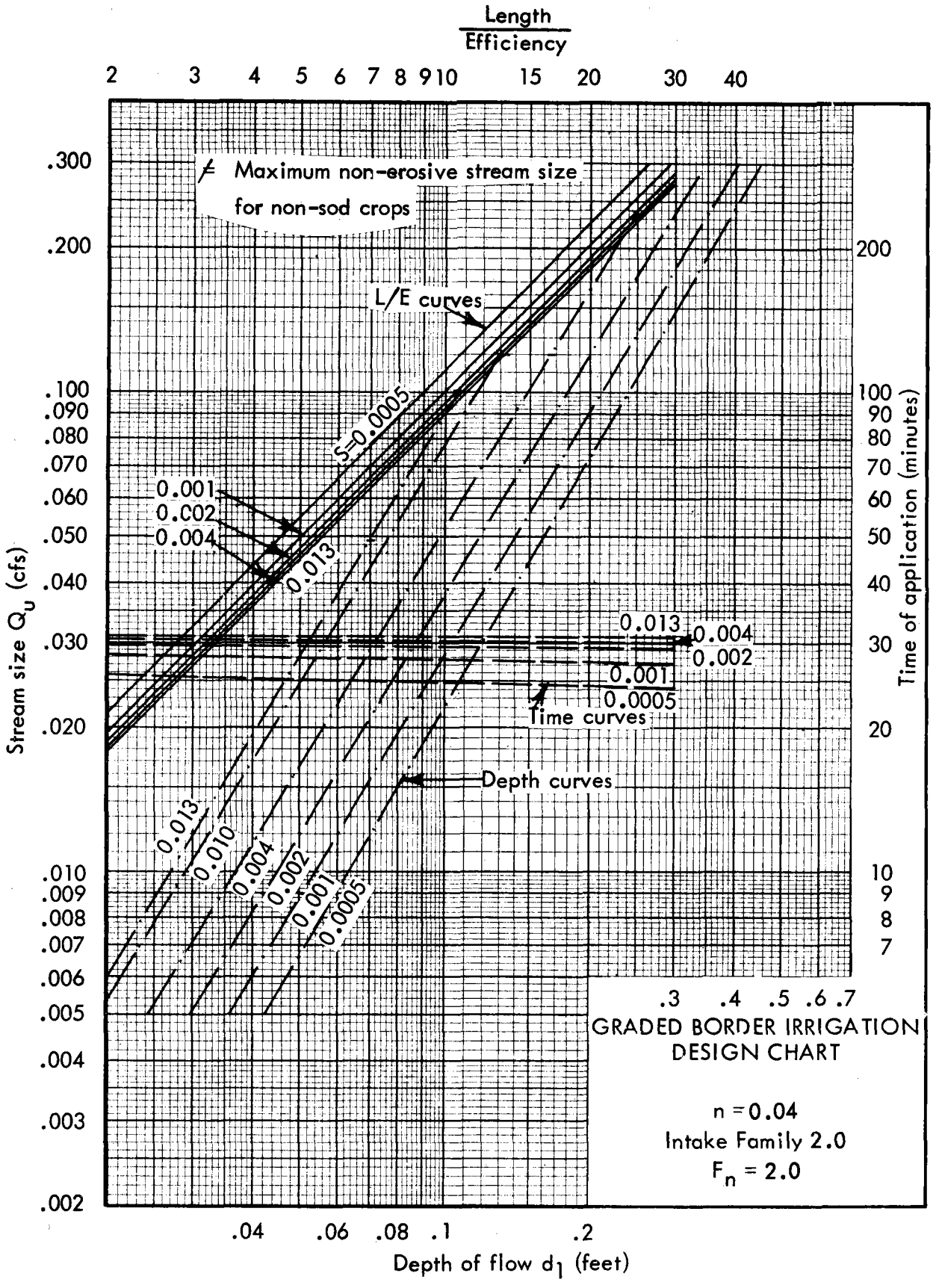

Lengt
Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
Time curves
Depth curves
S=0.0005
0.007
0.001
0.002
0.007
0.002
0.001
0.0005
0.007
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

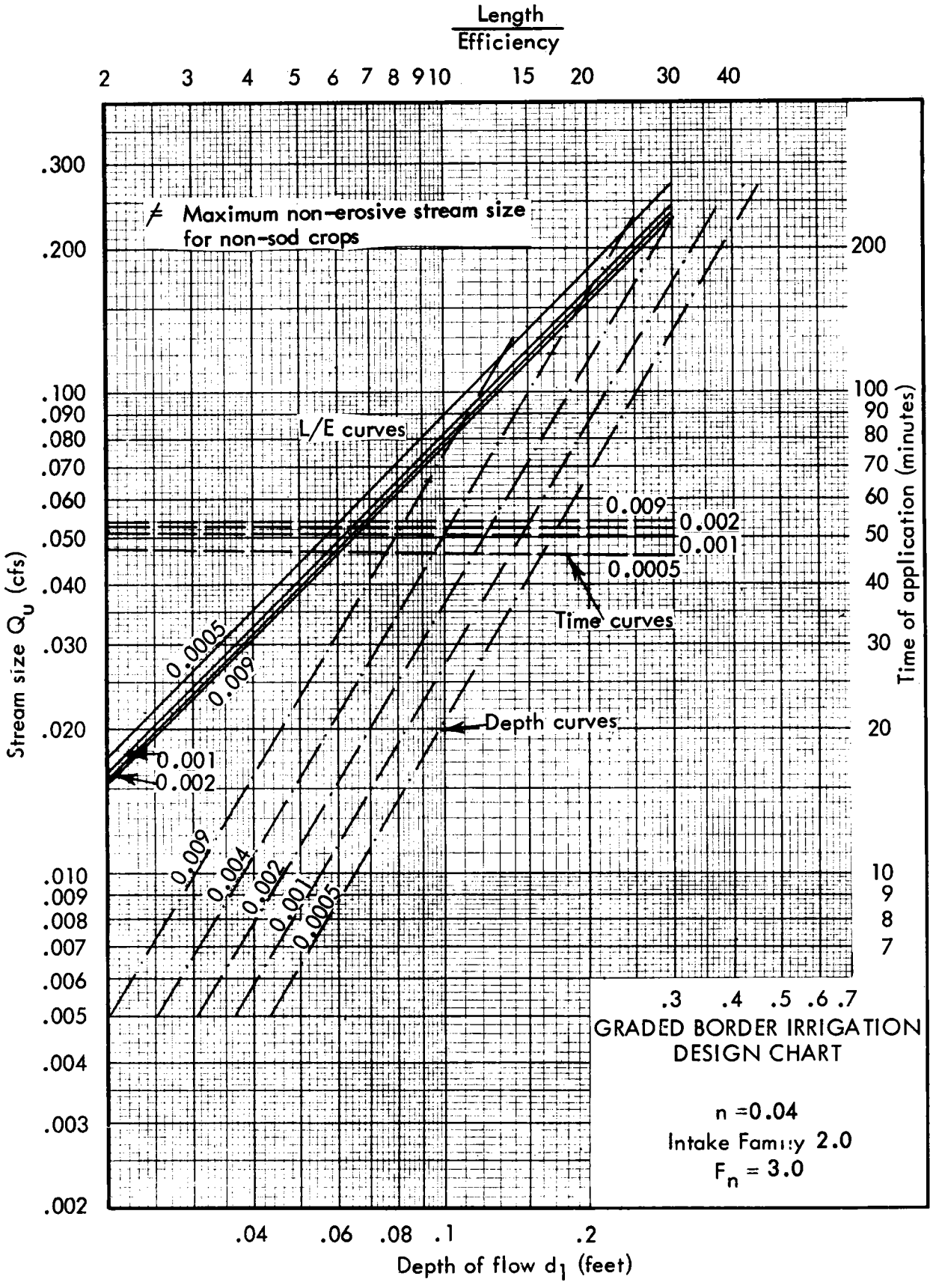

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.001
0.005
0.0005
L/E Curves
Depth curves
S=0.0005
0.005
0.001
0.005
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

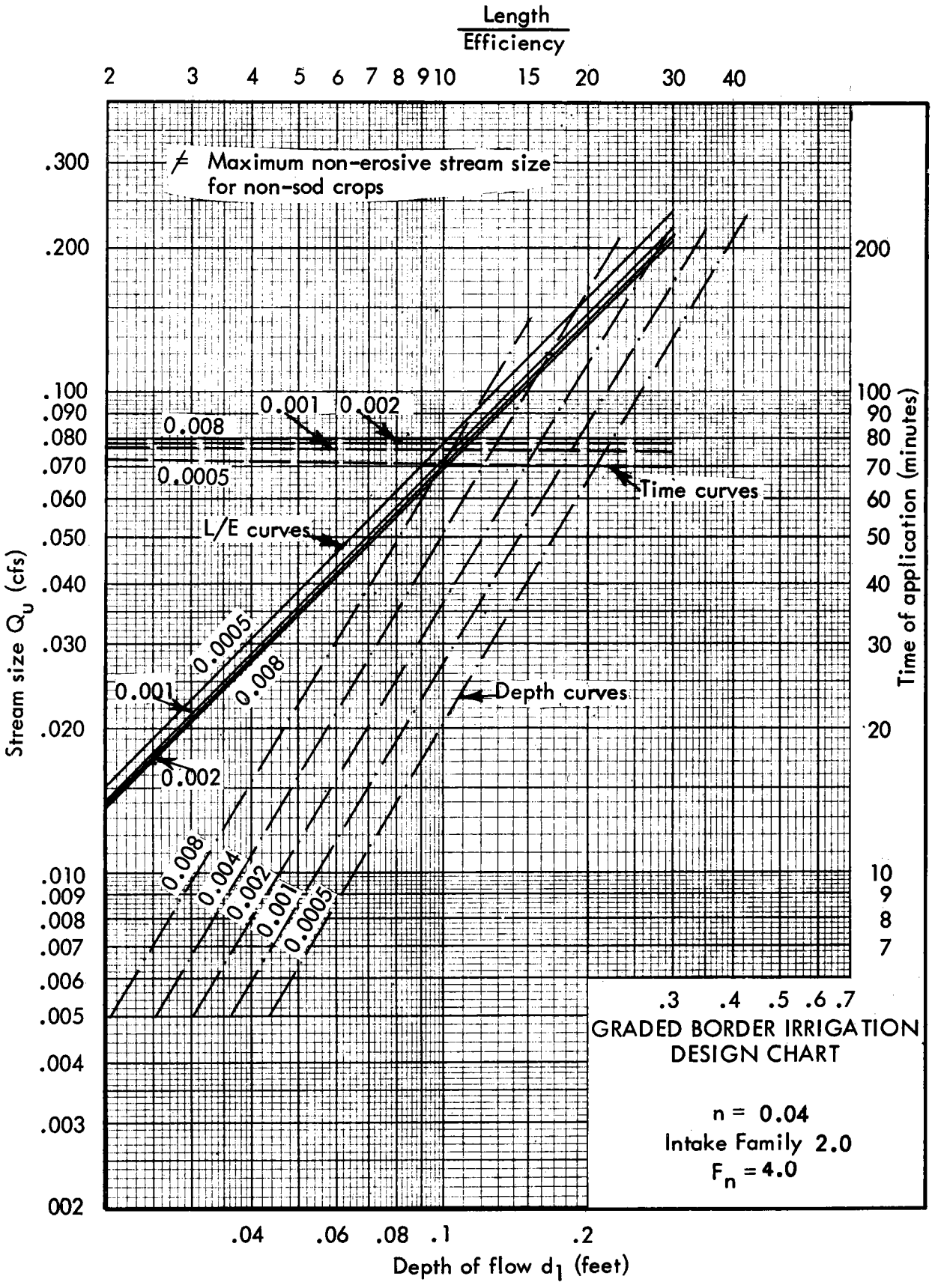

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.004
0.0005
0.001
L/E curves
0.001
S=0.0005
0.004
Depth curves
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 1.5
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

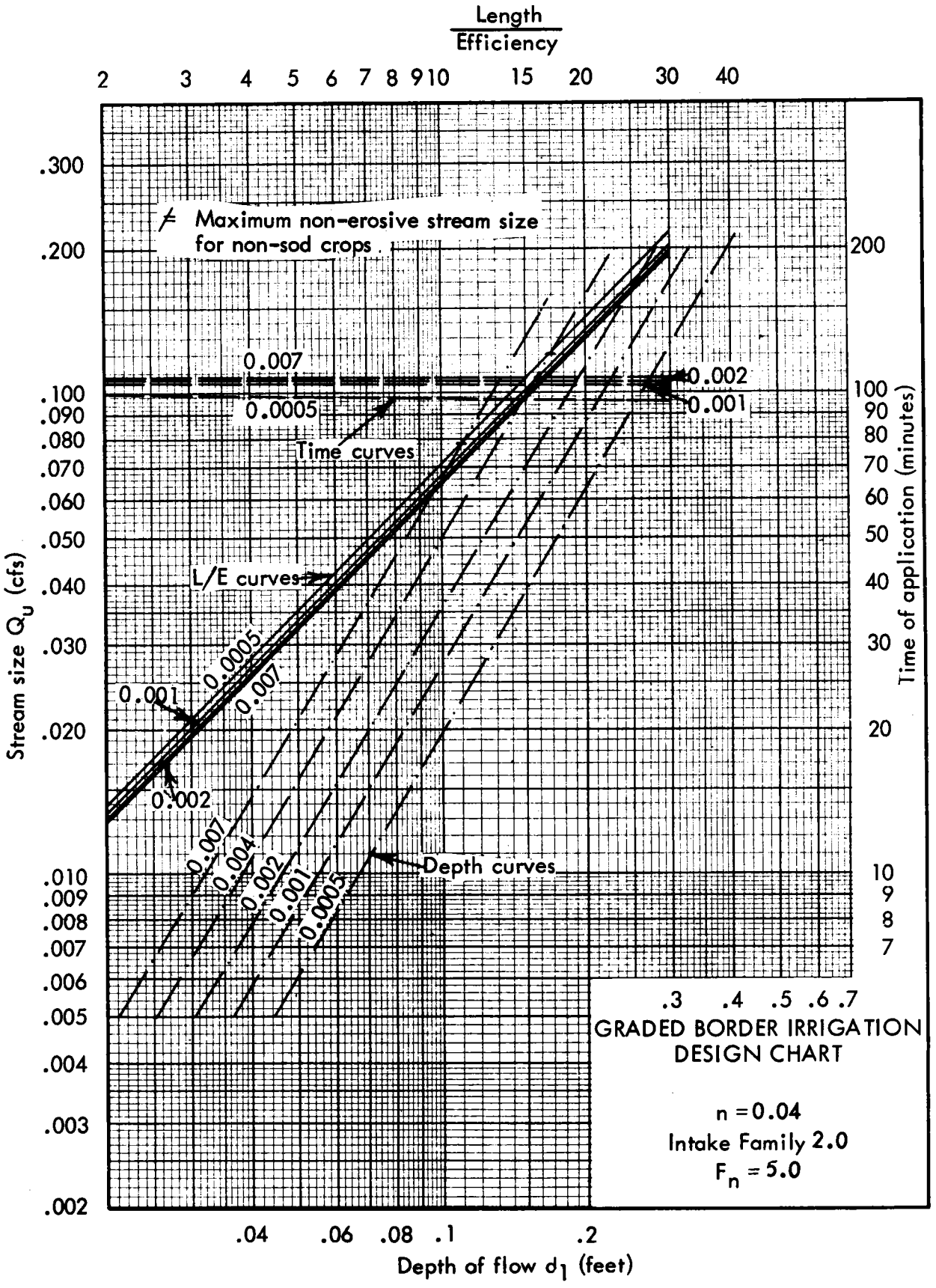

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
Time curves
0.004
0.001
0.0005
L/E curves
S=0.0005
0.004
0.001
Depth curves
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
200 100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n =0.04
Intake Family 1.5
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

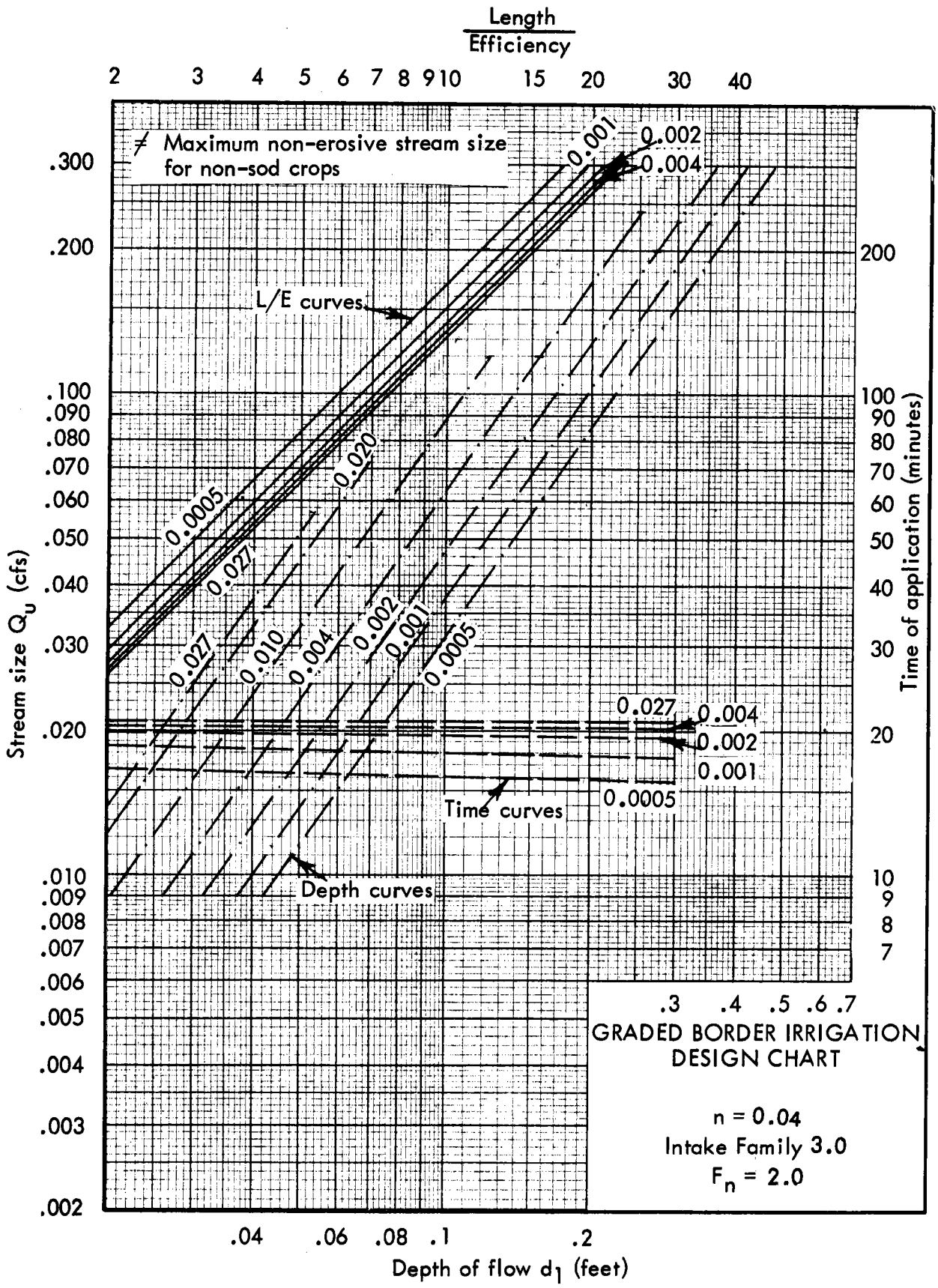

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
S=0.0005
0.001
0.002
0.004
0.027
0.020
0.010
0.004
0.002
0.001
0.0005
Depth curves
Time curves
0.027
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
200 100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

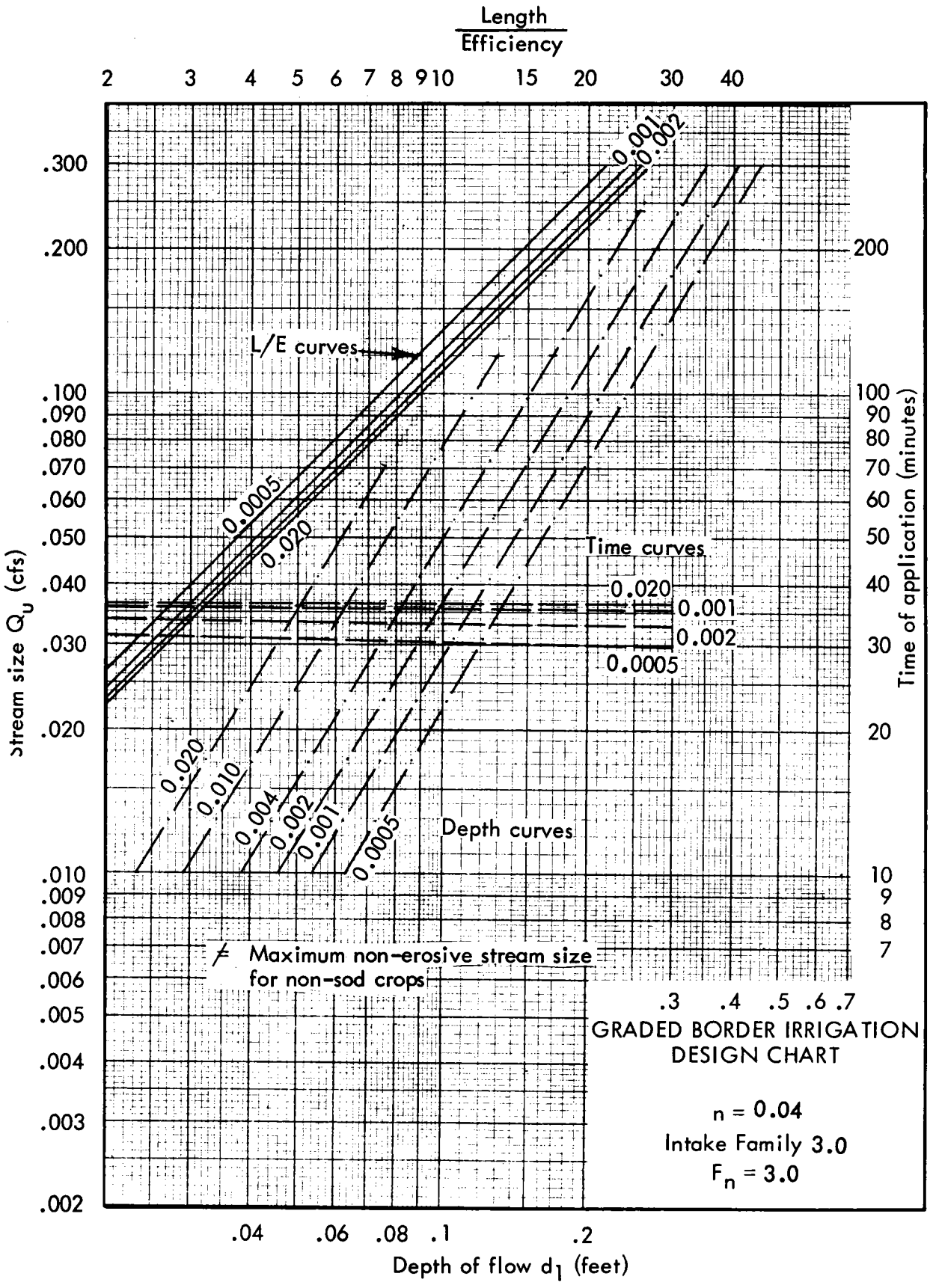

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
L/E curves
S=0.0005
0.001
0.002
0.004
0.013
0.013
0.004
0.002
0.001
0.0005
Time curves
Depth curves
0.013
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

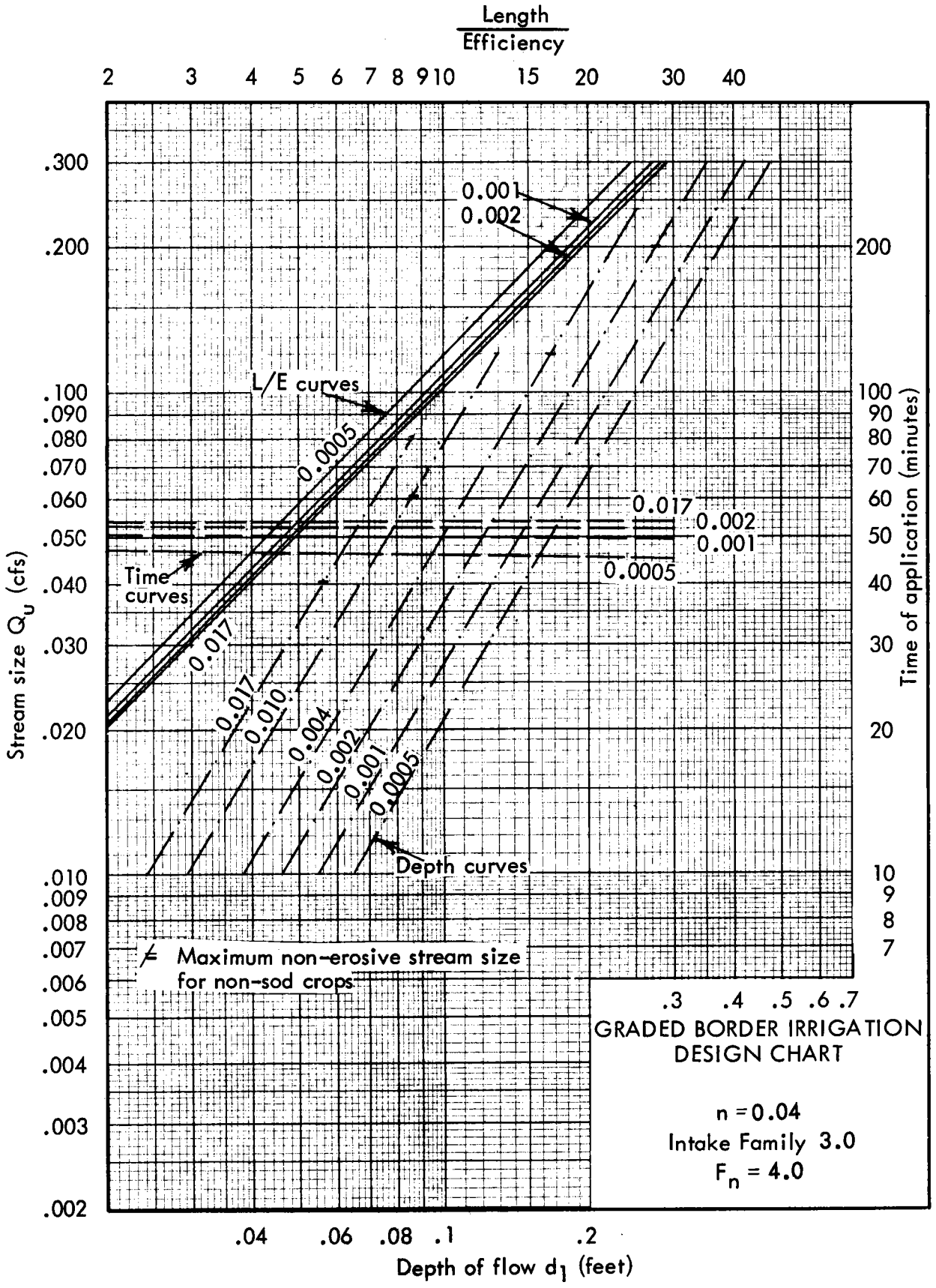

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
L/E curves
Time curves
Depth curves
0.009
0.002
0.001
0.0005
0.004
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 3.0

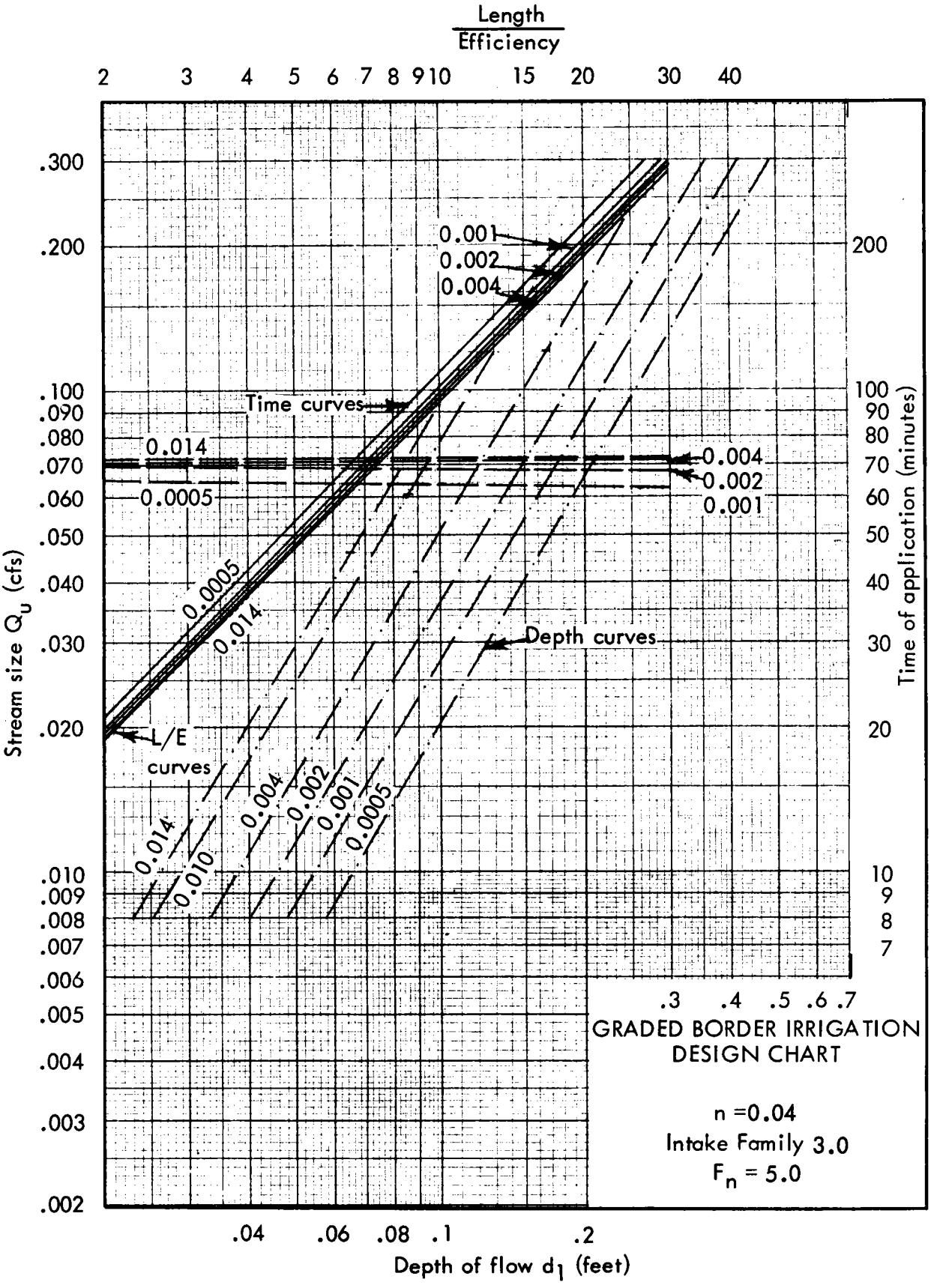

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.001
0.002
0.008
0.0005
L/E curves
Time curves
Depth curves
0.0005
0.008
0.001
0.002
0.008
0.004
0.002
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

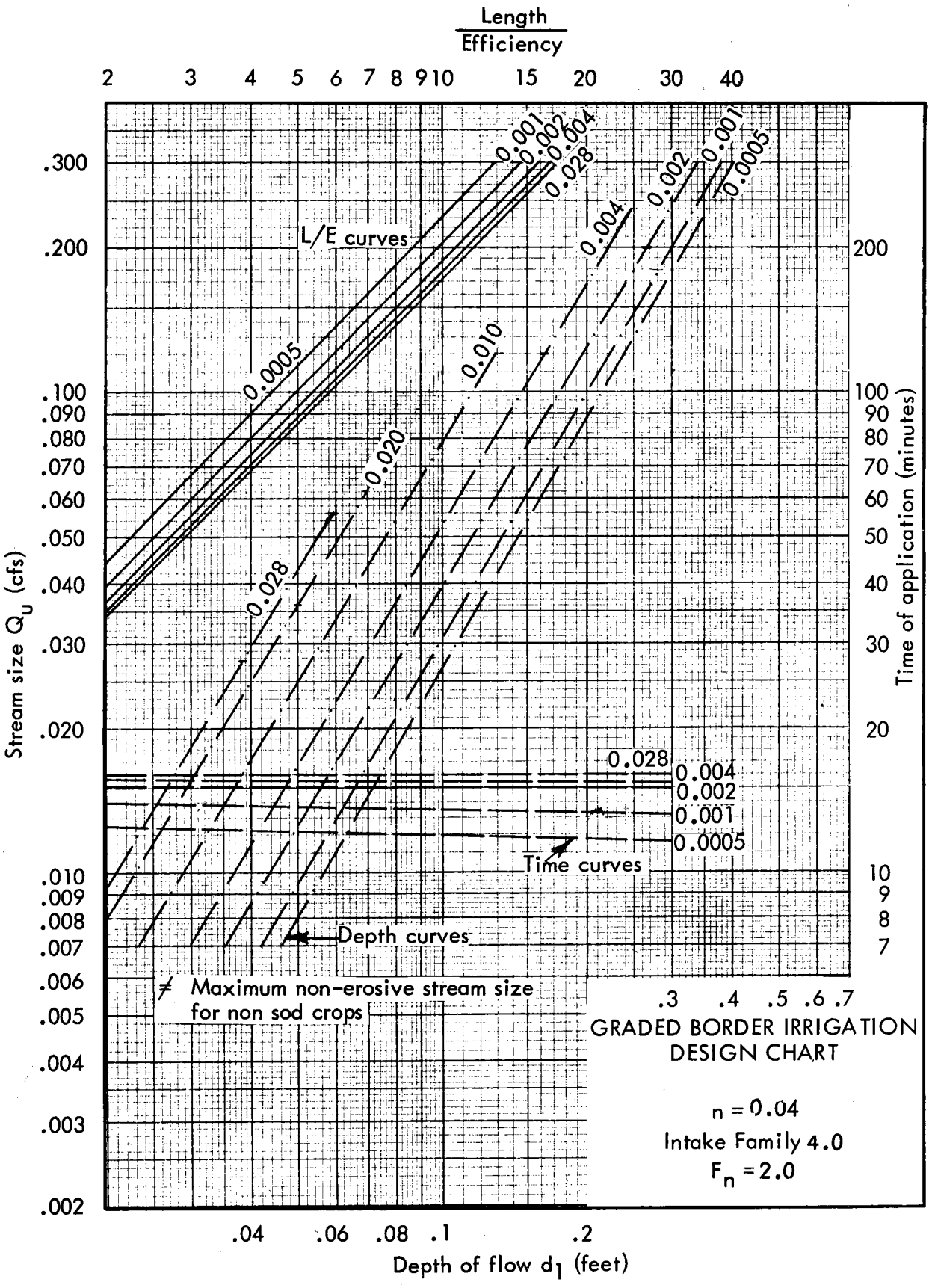

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
0.007
0.0005
0.002
0.001
Time curves
L/E curves
0.0005
0.007
0.001
0.002
0.007
0.004
0.002
0.001
0.0005
Depth curves
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 2.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

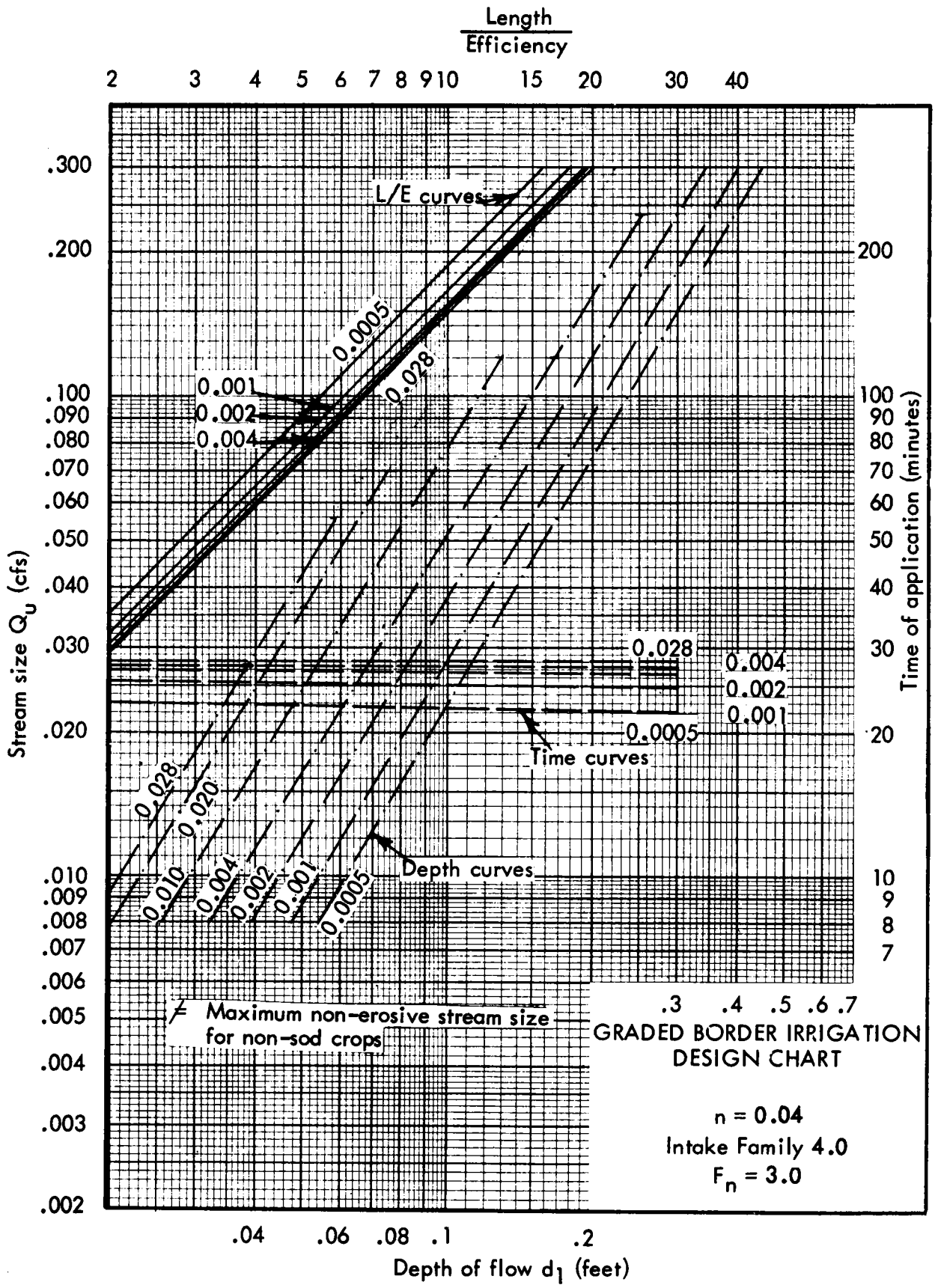

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
0.001
0.002
0.004
L/E curves
0.0005
0.027
0.020
0.027
0.010
0.004
0.002
0.001
0.0005
0.027
0.004
0.002
0.001
0.0005
Time curves
Depth curves
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

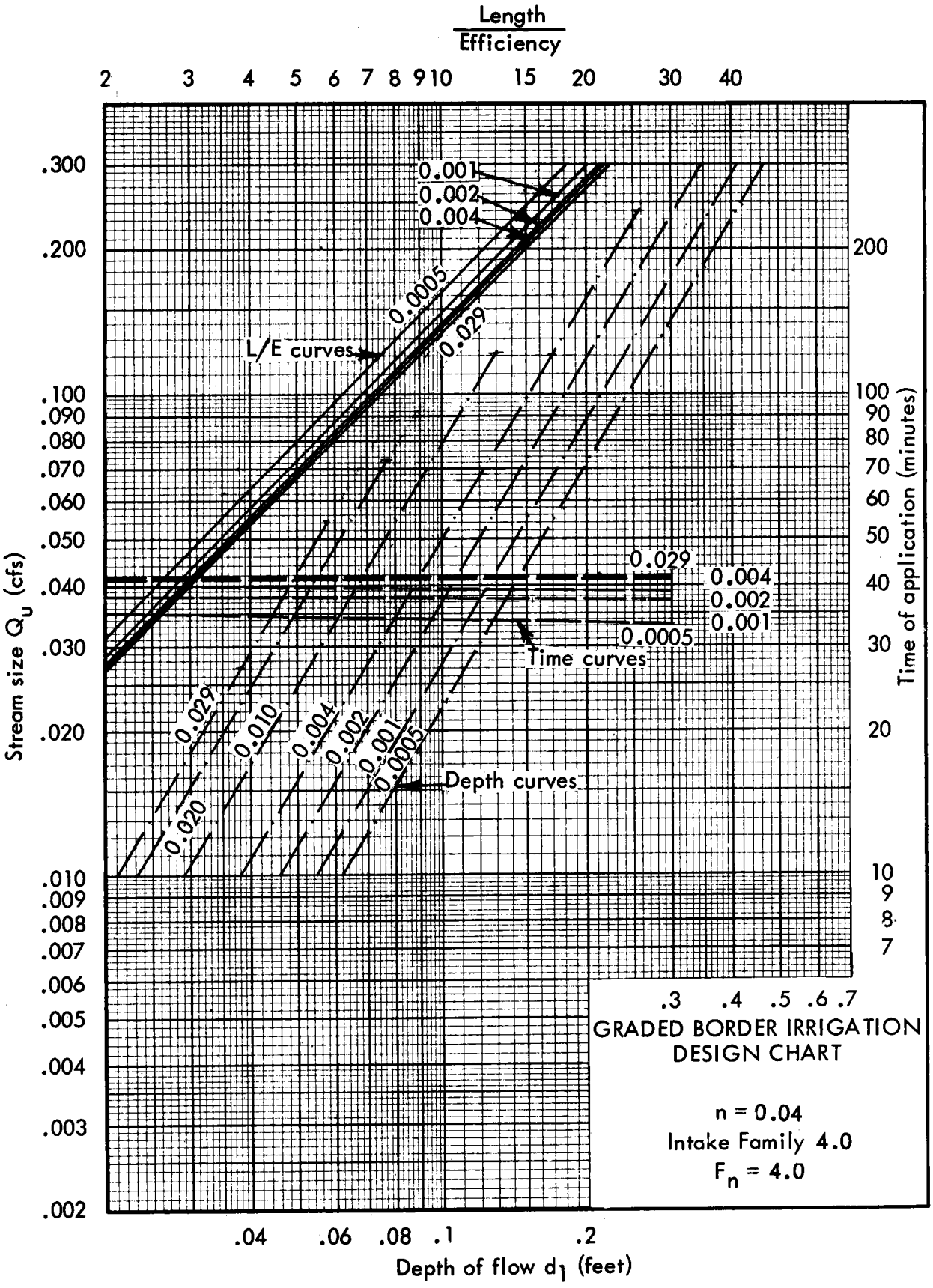

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.001
0.002
L/E curves
0.0005
0.020
Time curves
0.020
0.001
0.002
0.0005
0.020
0.010
0.004
0.002
0.001
0.0005
Depth curves
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

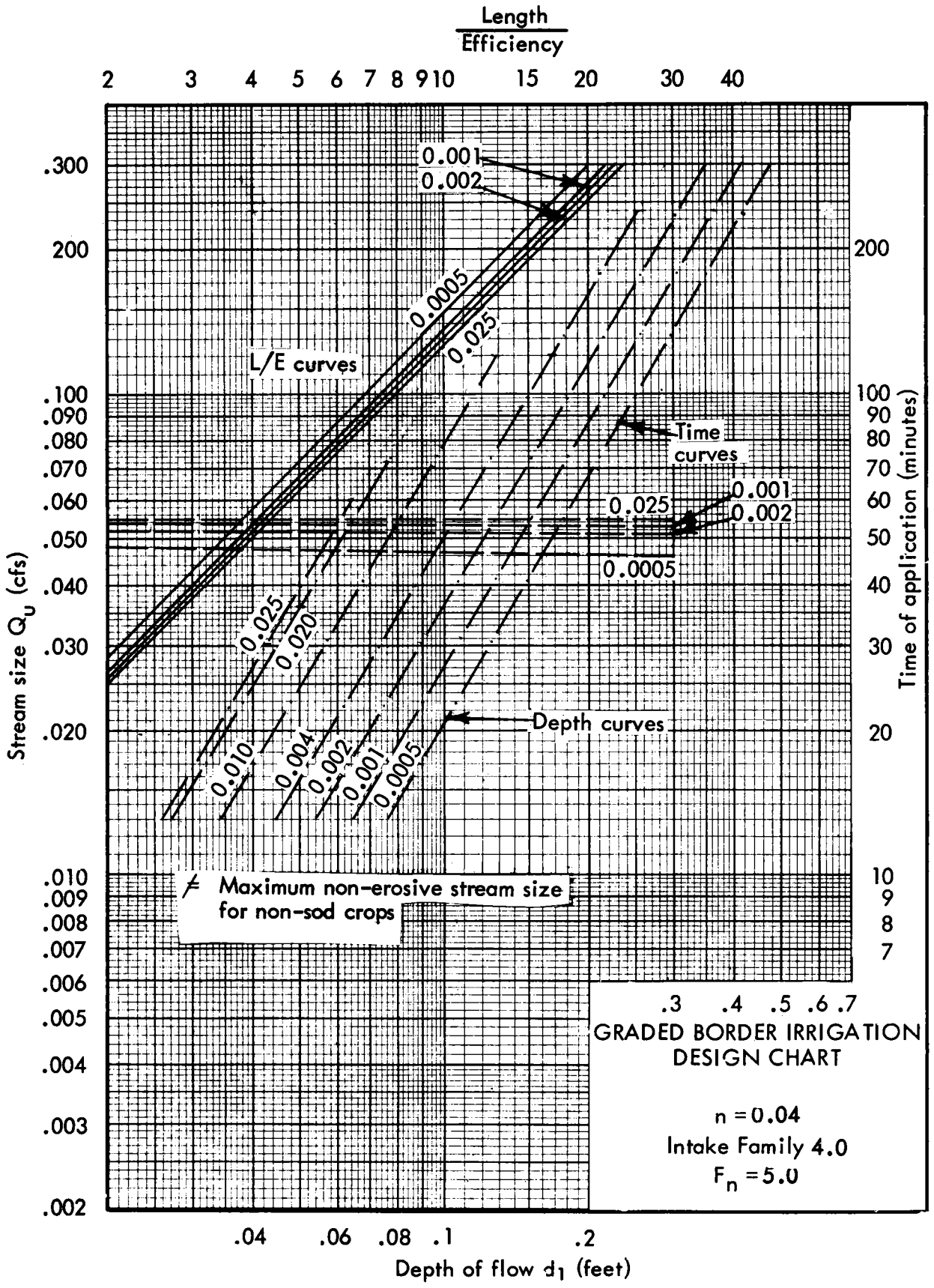

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.001
0.002
L/E curves
0.0005
0.017
0.002
0.001
0.0005
Time curves
0.017
0.017
0.010
0.004
0.002
0.001
0.0005
Depth curves
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 3.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

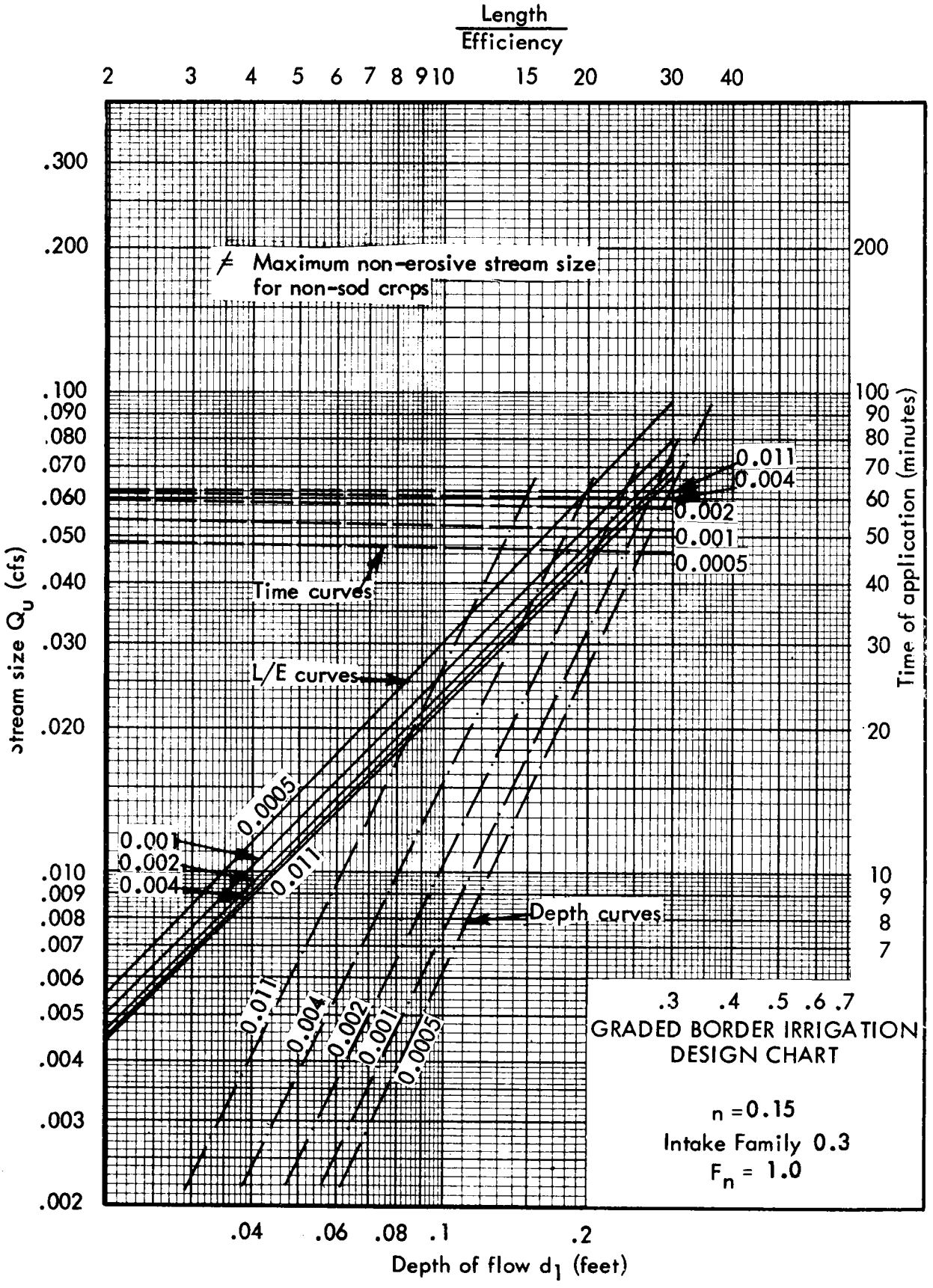

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.001
0.002
0.004
Time curves
0.014
0.0005
0.0005
0.014
Depth curves
L/E curves
0.014
0.010
0.004
0.002
0.001
0.0005
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n =0.04
Intake Family 3.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

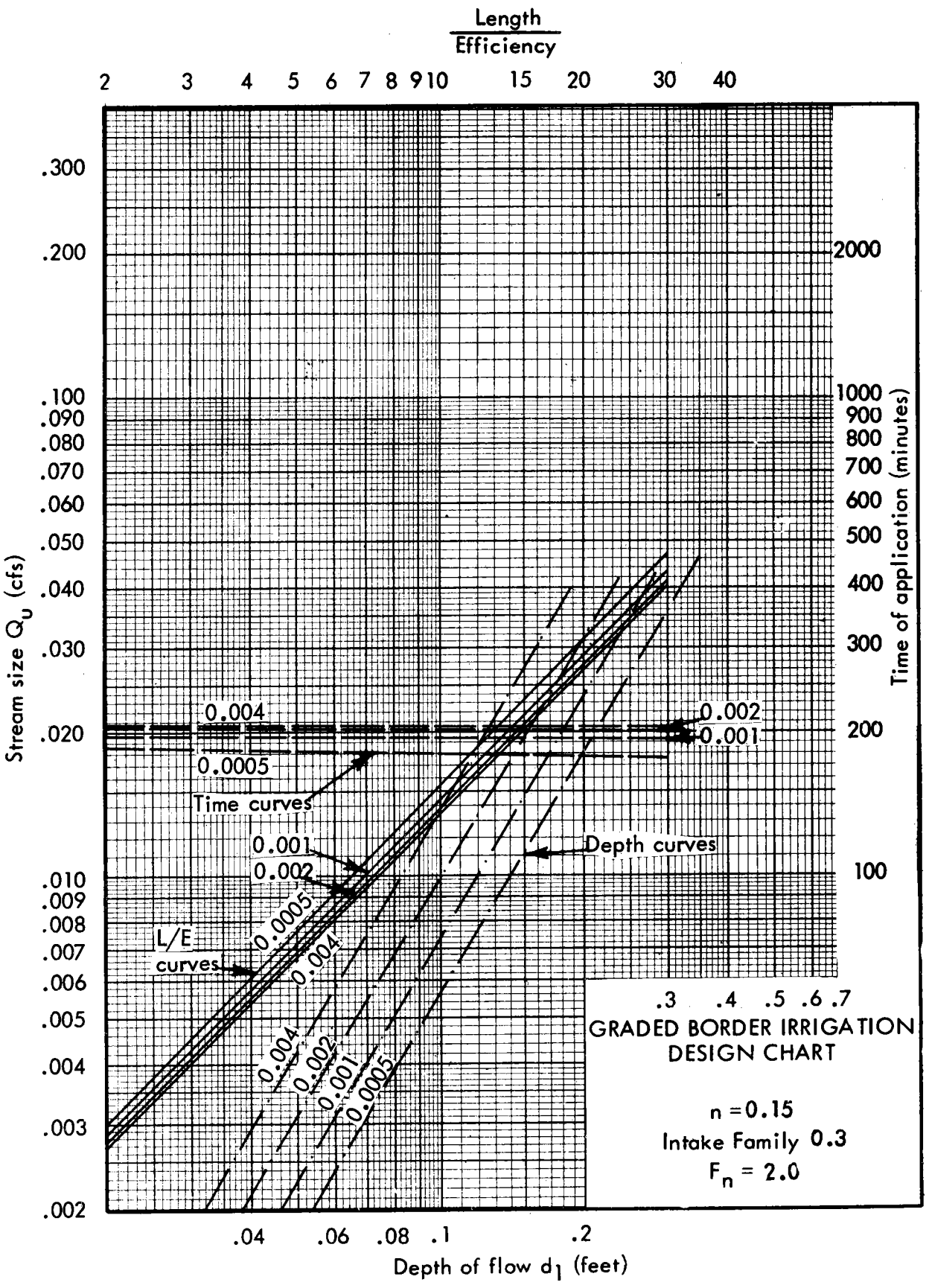

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
L/E curves
0.001
0.002
0.004
0.028
0.0005
0.010
0.020
0.028
0.004
0.002
0.001
0.0005
Time curves
Depth curves
≠ Maximum non-erosive stream size for non sod crops
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
200 100 90 80 70 60 50 40 30 20 10 9 8 7
.04 .06 .08 .1 .2 .3 .4 .5 .6 .7
Depth of flow d_1 (feet)
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 2.0

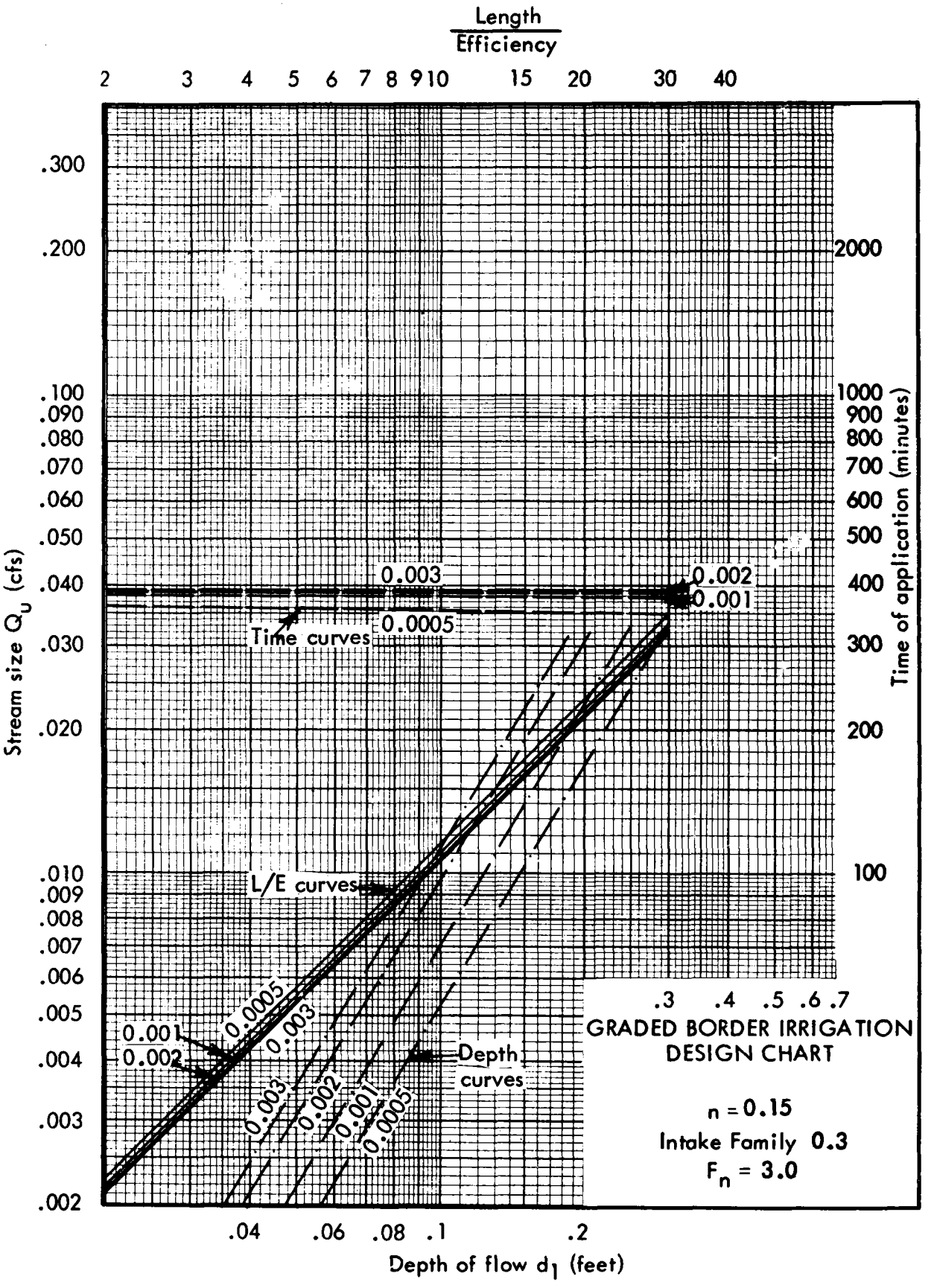

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
L/E curves
0.0005
0.028
0.001
0.002
0.004
0.028
0.004
0.002
0.001
0.0005
Time curves
0.028
0.020
0.010
0.004
0.002
0.001
0.0005
Depth curves
Maximum non-erosive stream size for non-sod crops
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 3.0
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
200 100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

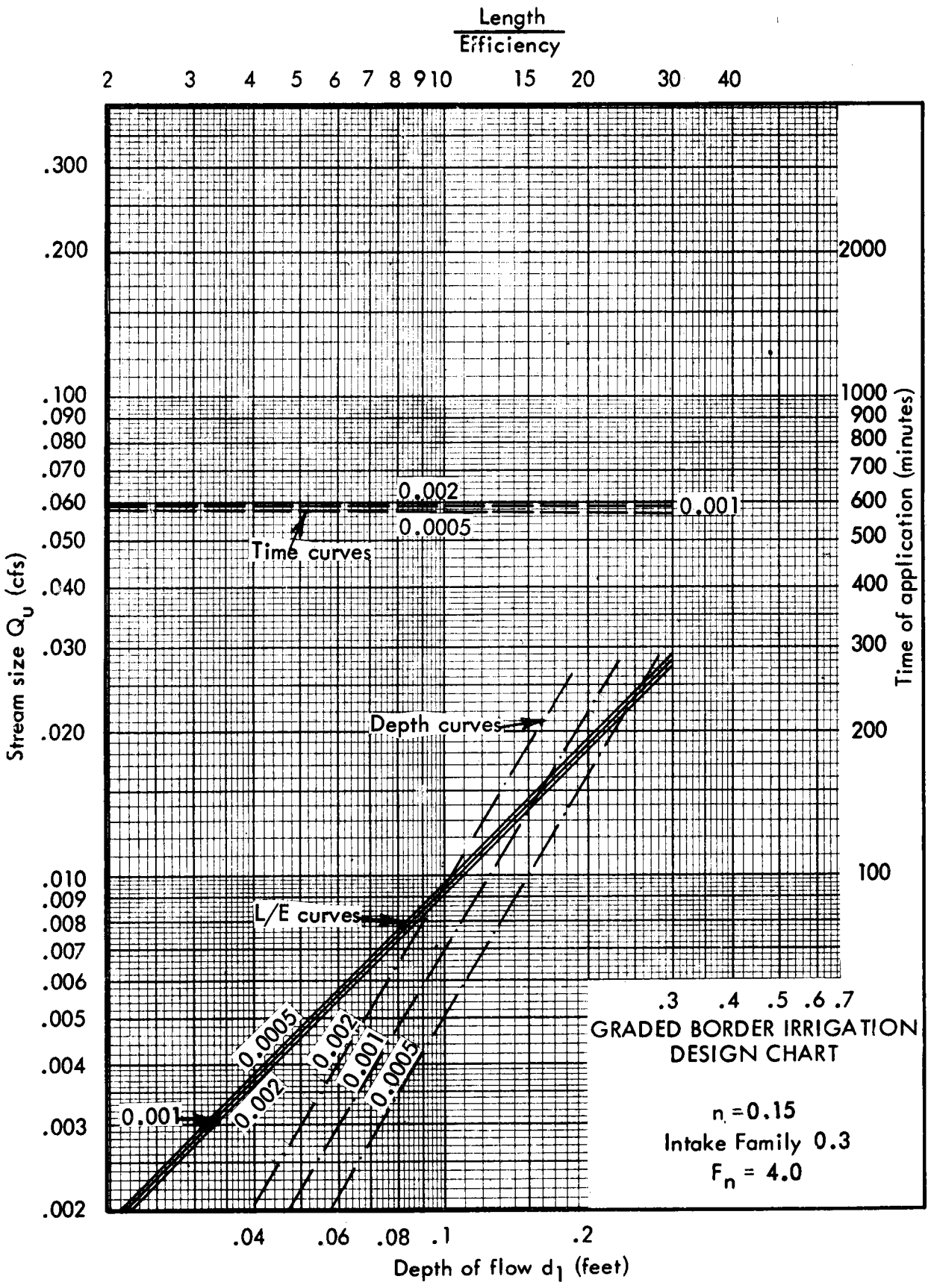

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.001
0.002
0.004
0.0005
0.029
L/E curves
0.029
0.004
0.002
0.001
0.0005
Time curves
0.029
0.010
0.004
0.002
0.001
0.0005
0.020
Depth curves
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

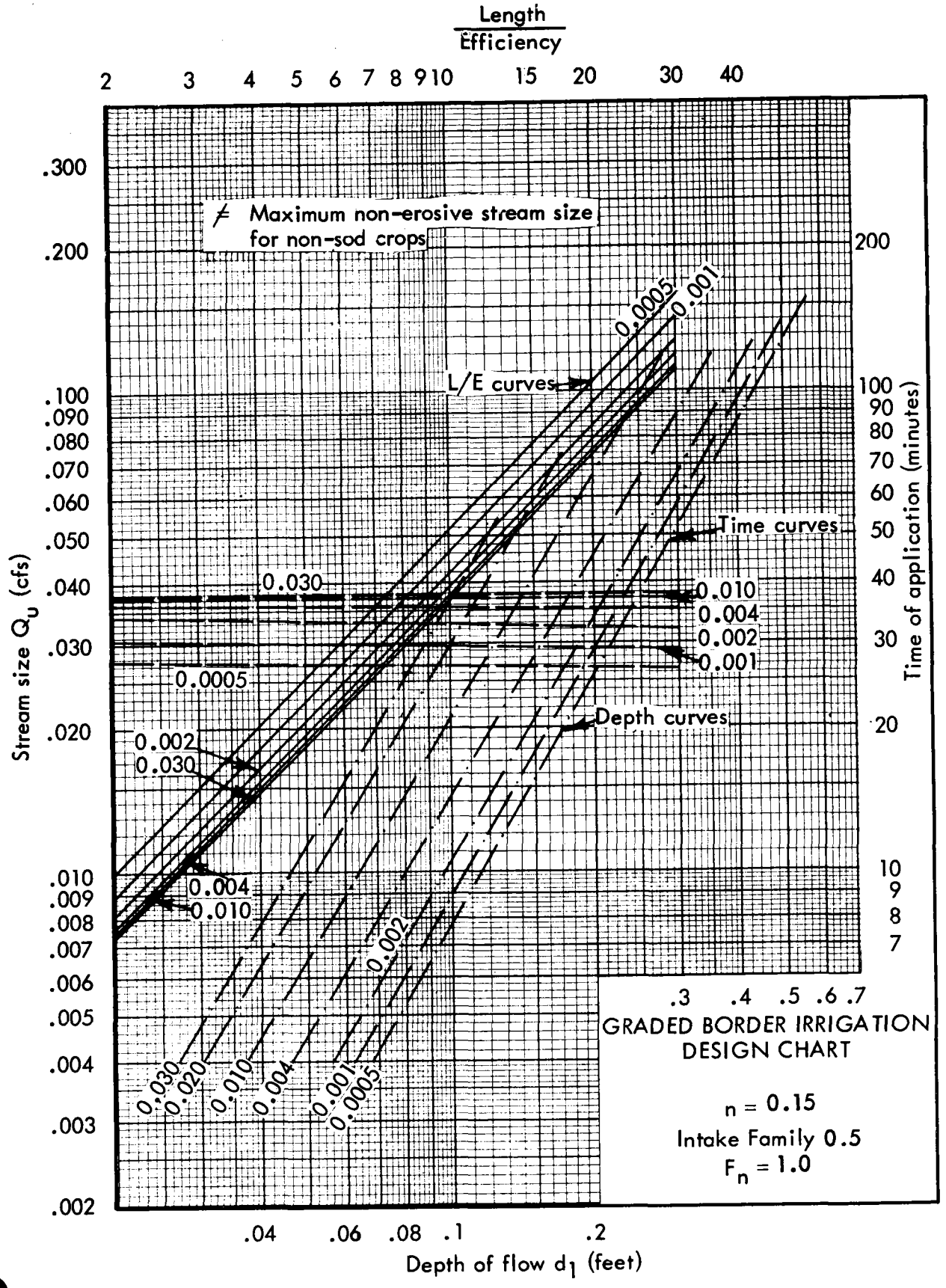

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
0.001
0.002
0.0005
0.025
L/E curves
Time curves
0.025
0.001
0.002
0.0005
0.025
0.020
0.010
0.004
0.002
0.001
0.0005
Depth curves
≠ Maximum non-erosive stream size for non-sod crops
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.04
Intake Family 4.0
F_n = 5.0

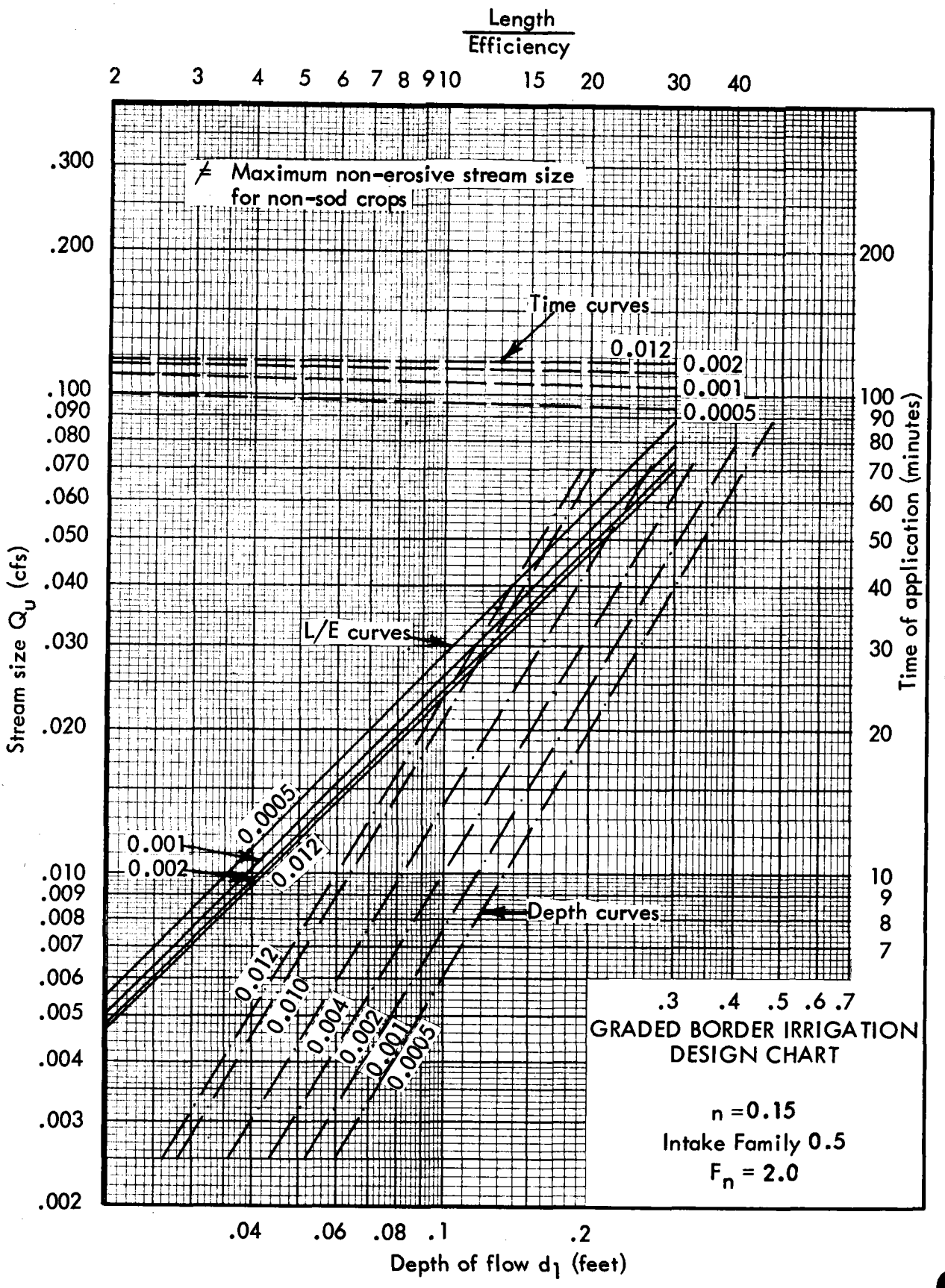

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
≠ Maximum non-erosive stream size for non-sod crops
Time curves
L/E curves
Depth curves
0.011
0.004
0.002
0.001
0.0005
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

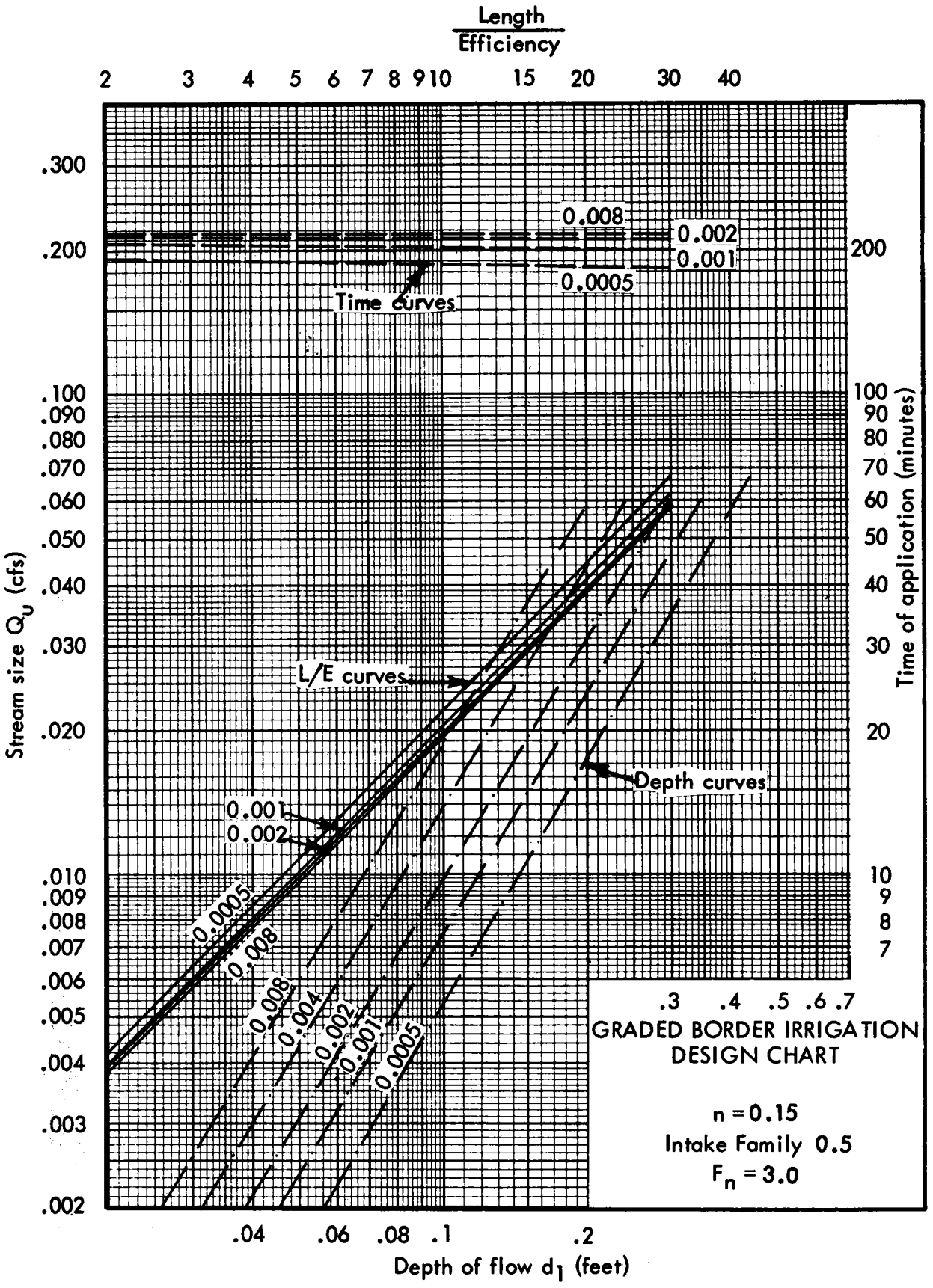

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.004
0.0005
0.002
0.001
Time curves
0.001
0.002
0.0005
0.004
L/E curves
Depth curves
0.004
0.002
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

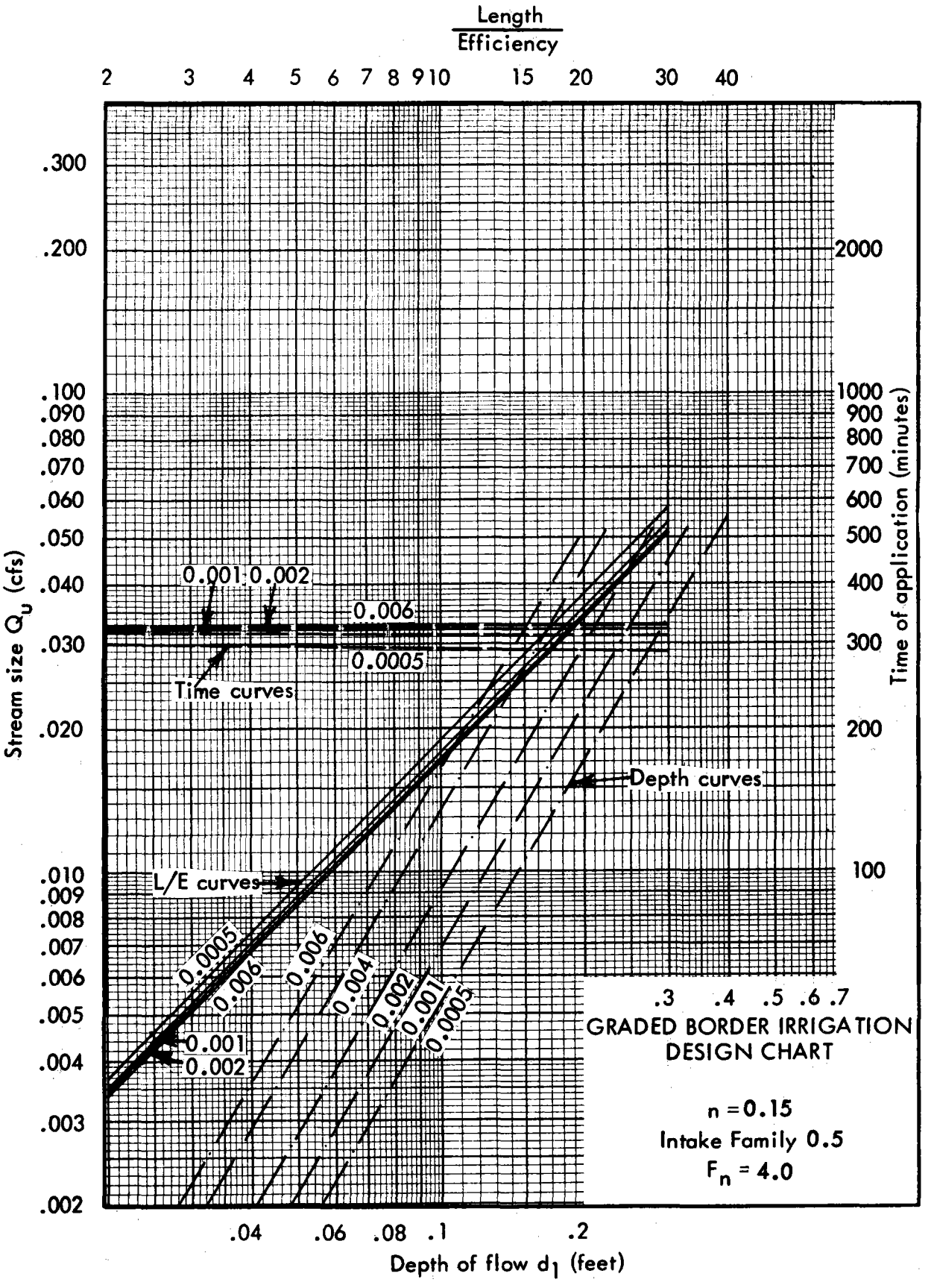

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.003
0.0005
0.002
0.001
Time curves
L/E curves
0.001
0.002
0.0005
0.003
0.003
0.002
0.001
0.0005
Depth curves
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

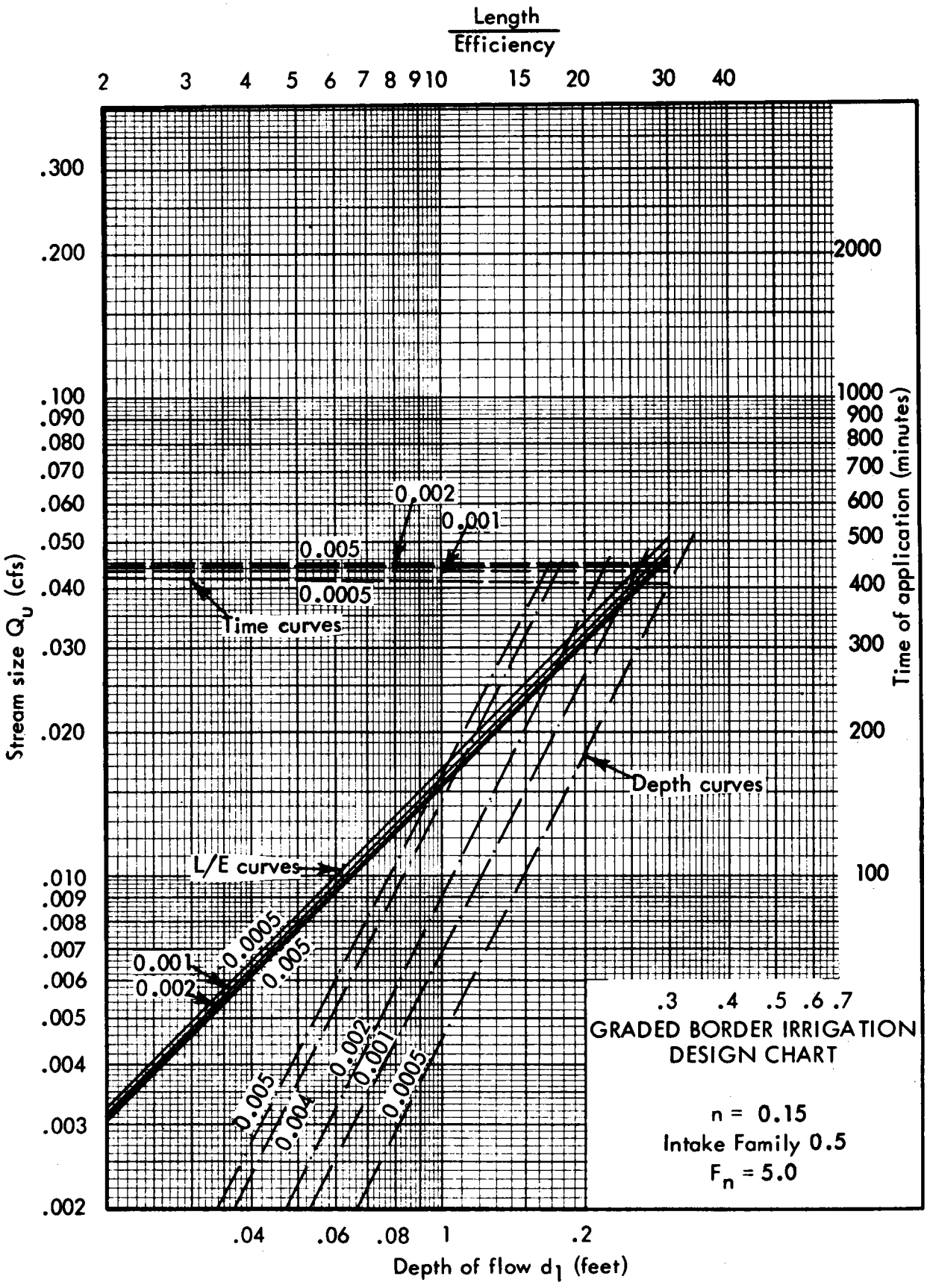

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.002
0.0005
0.001
Time curves
Depth curves
L/E curves
0.0005
0.002
0.001
0.002
0.001
0.0005
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.15
Intake Family 0.3
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

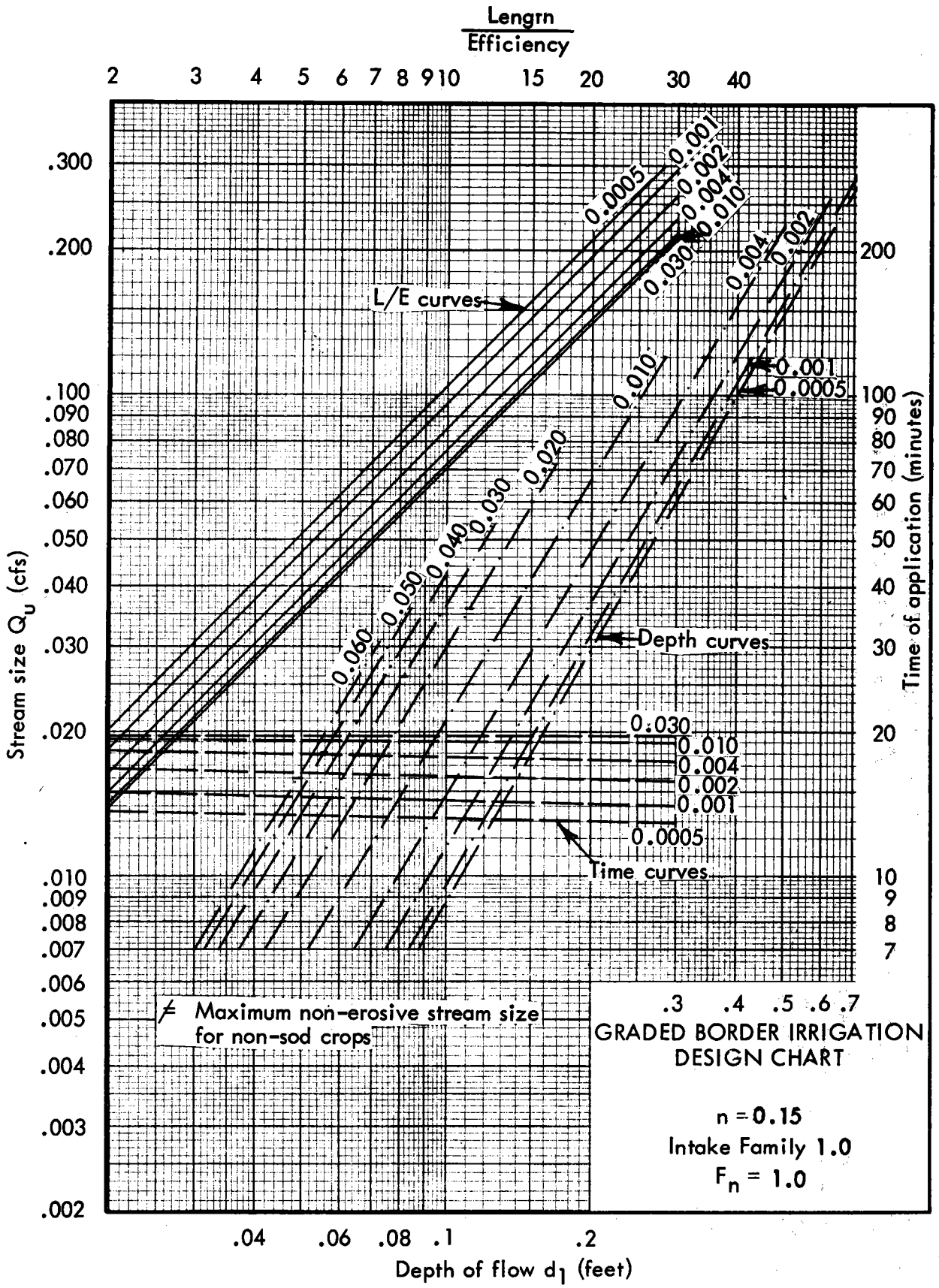

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
Time curves
Depth curves
0.0005
0.001
0.030
0.010
0.004
0.002
0.001
0.0005
0.002
0.030
0.004
0.010
0.002
0.030
0.020
0.010
0.004
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

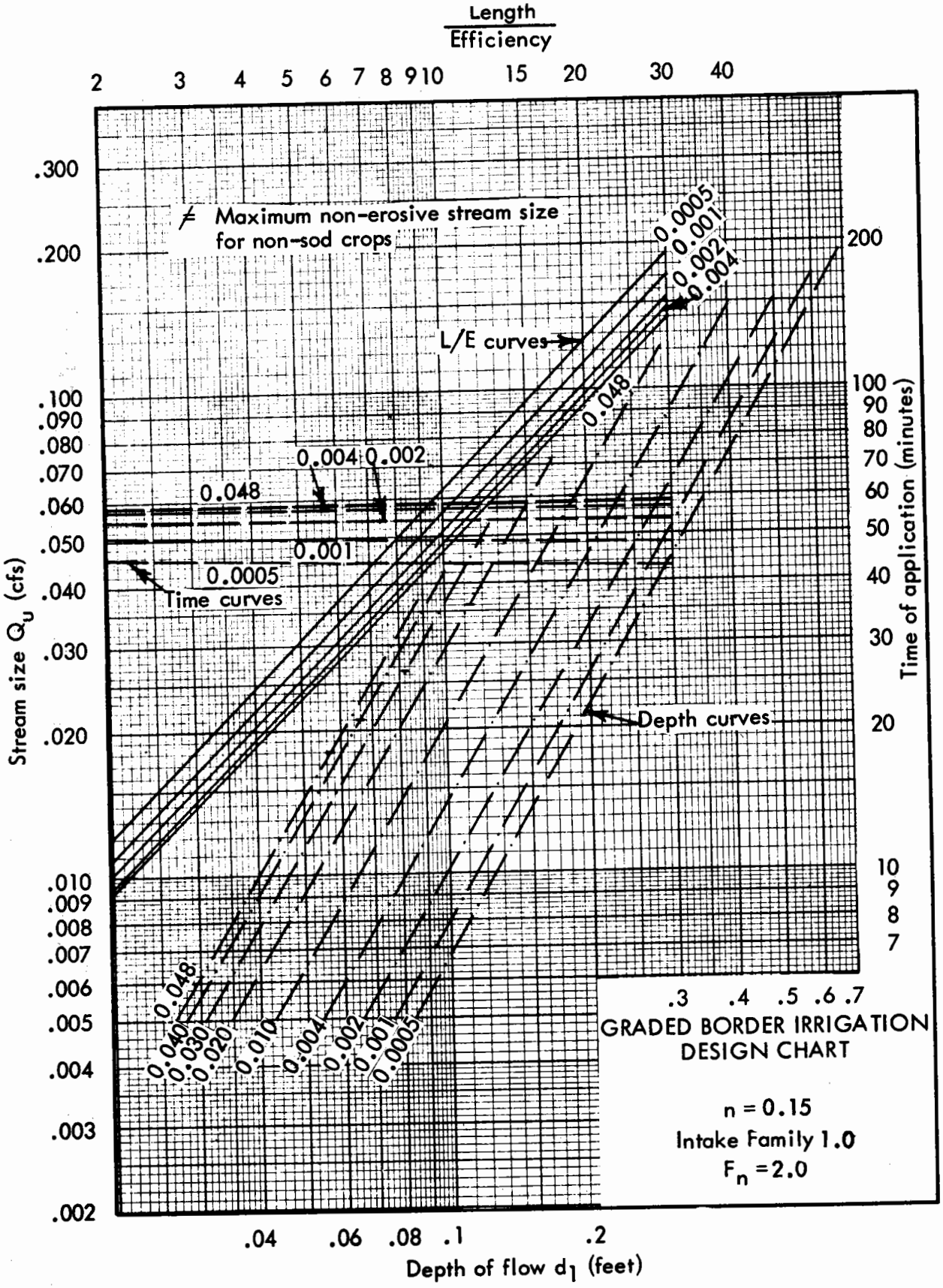

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.012
0.002
0.001
0.0005
L/E curves
0.0005
0.001
0.002
0.012
Depth curves
0.012
0.010
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

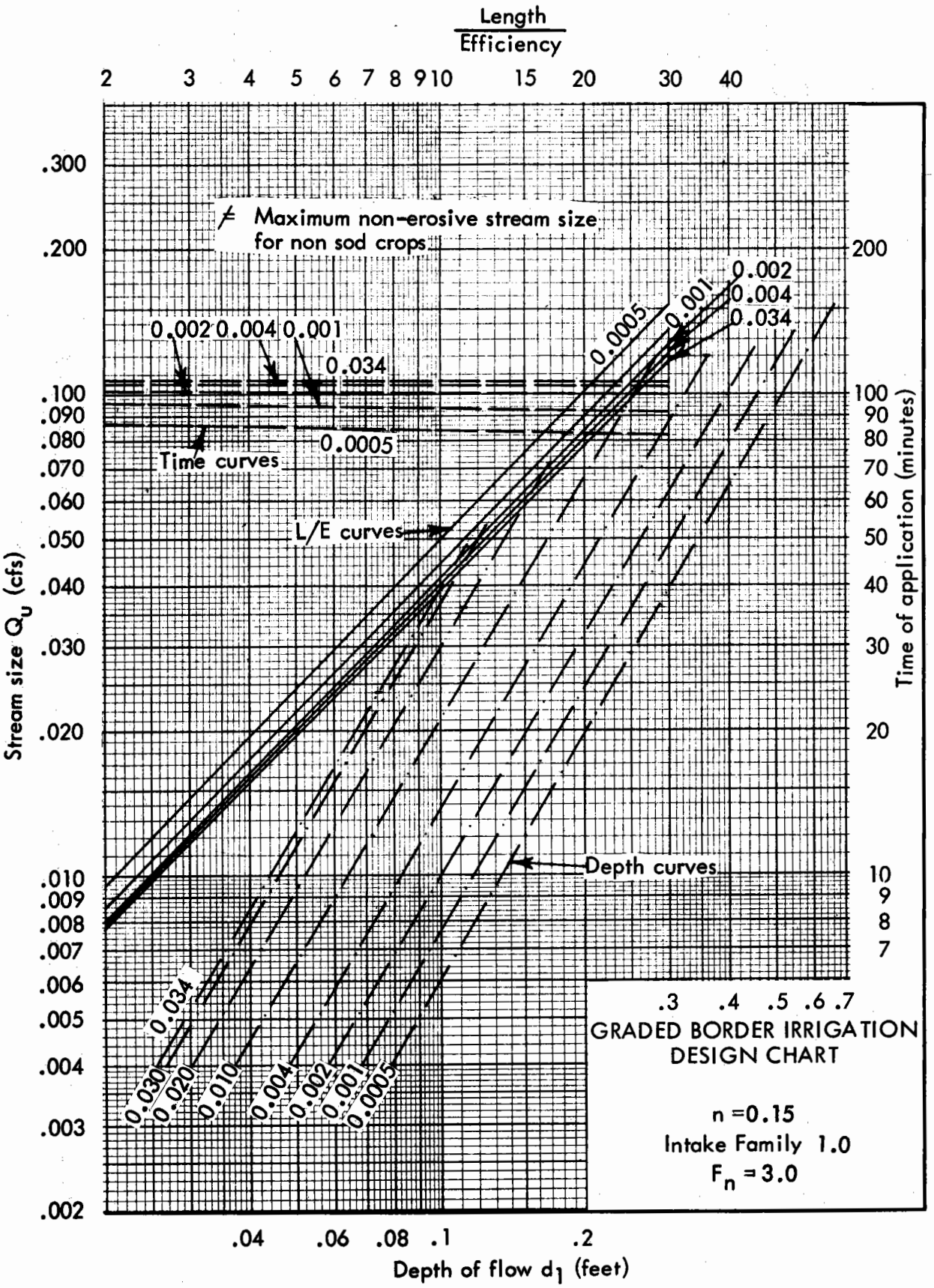

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.008
0.002
0.001
0.0005
Time curves
L/E curves
Depth curves
0.001
0.002
0.0005
0.008
0.008
0.004
0.002
0.001
0.0005
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

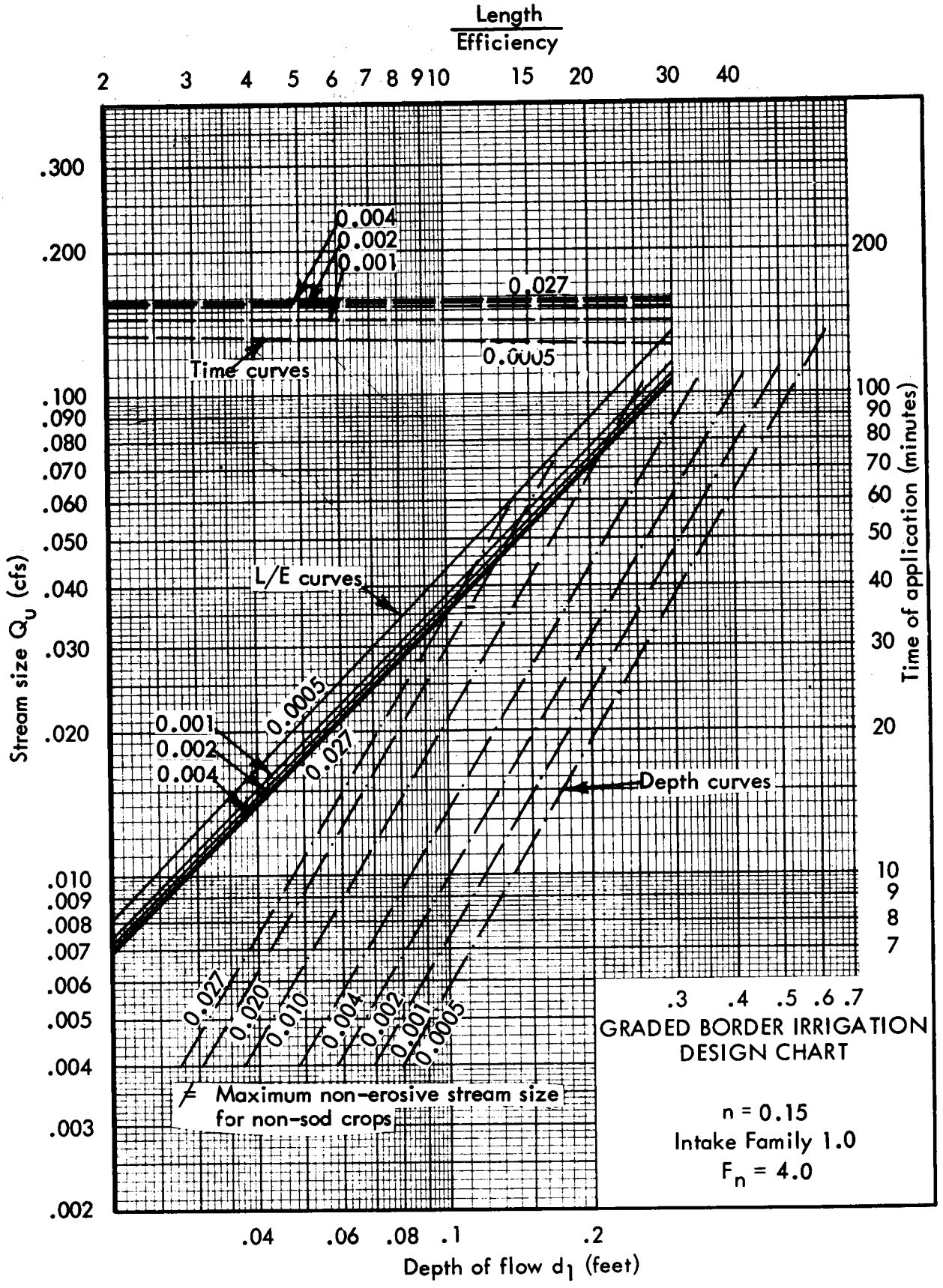

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.001 0.002
0.006
0.0005
Time curves
Depth curves
L/E curves
0.0005
0.006
0.006
0.004
0.002
0.001
0.0005
0.001
0.002
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

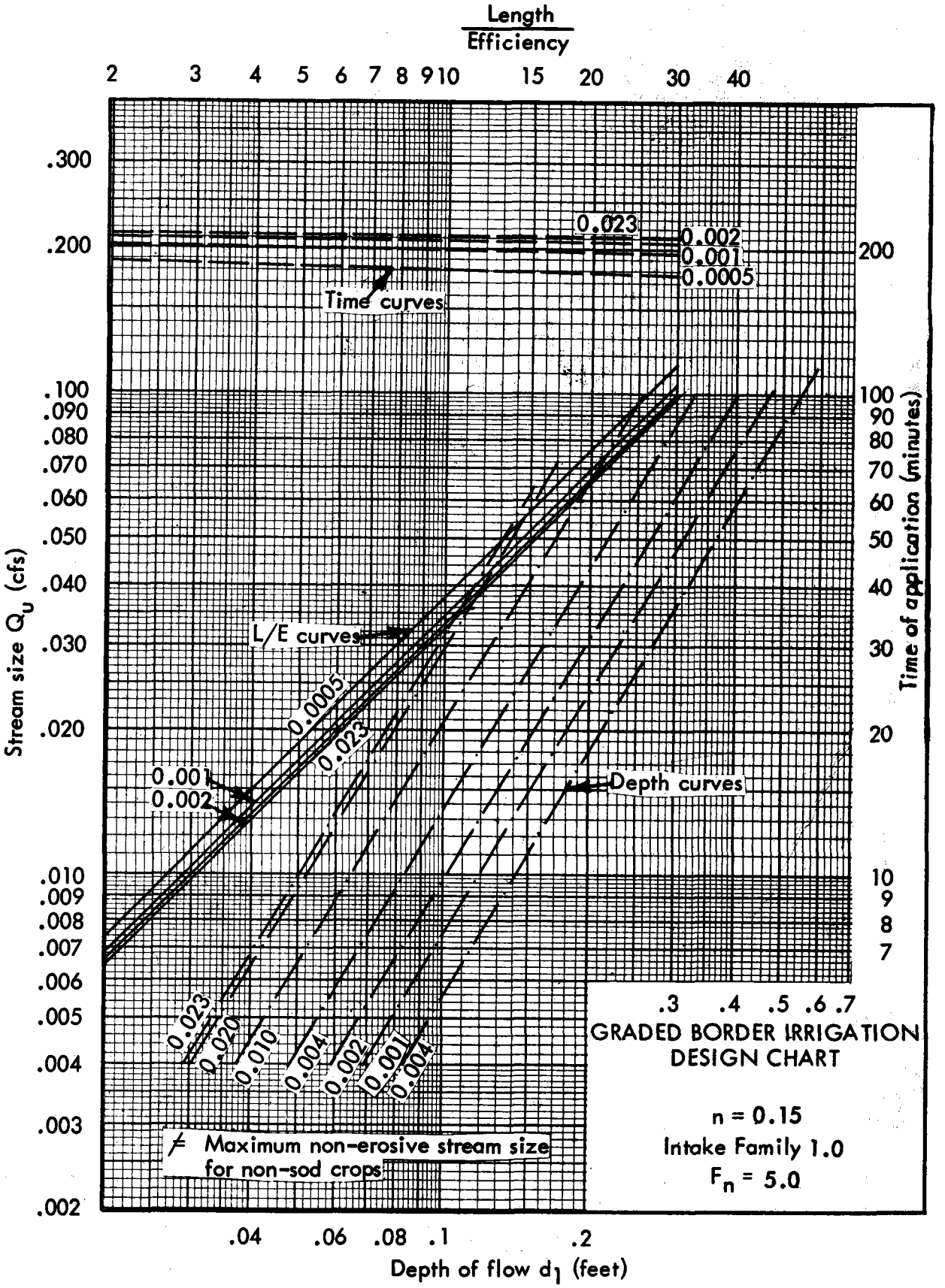

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.002
0.001
0.005
0.0005
Time curves
Depth curves
L/E curves
0.0005
0.005
0.001
0.002
0.005
0.004
0.002
0.001
0.0005
.04 .06 .08 1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.15
Intake Family 0.5
F_n = 5.0

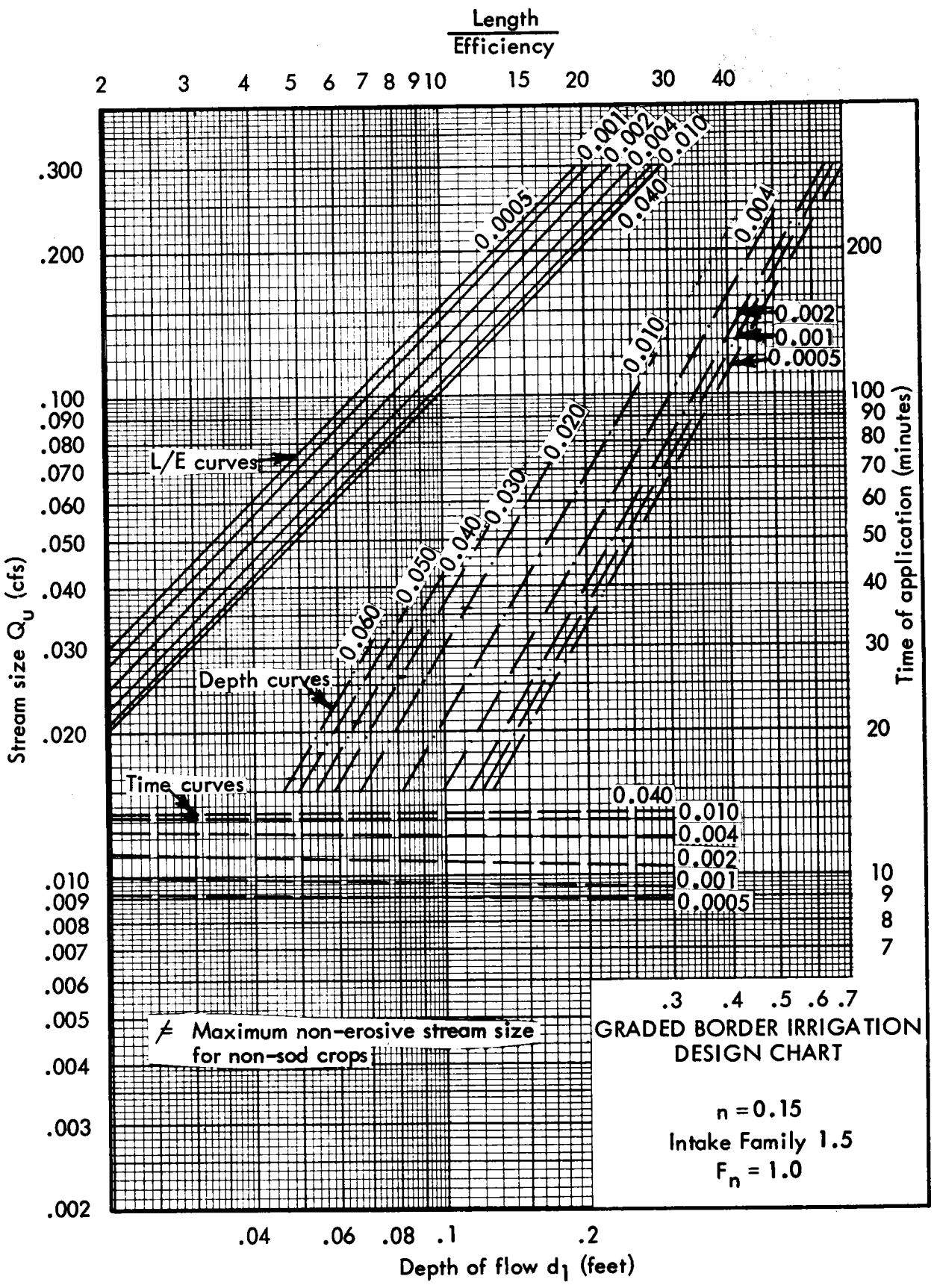

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
L/E curves
0.0005
0.001
0.002
0.004
0.010
0.030
0.004
0.002
0.001
0.0005
0.010
0.020
0.030
0.040
0.050
0.060
Depth curves
0.030
0.010
0.004
0.002
0.001
0.0005
Time curves
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

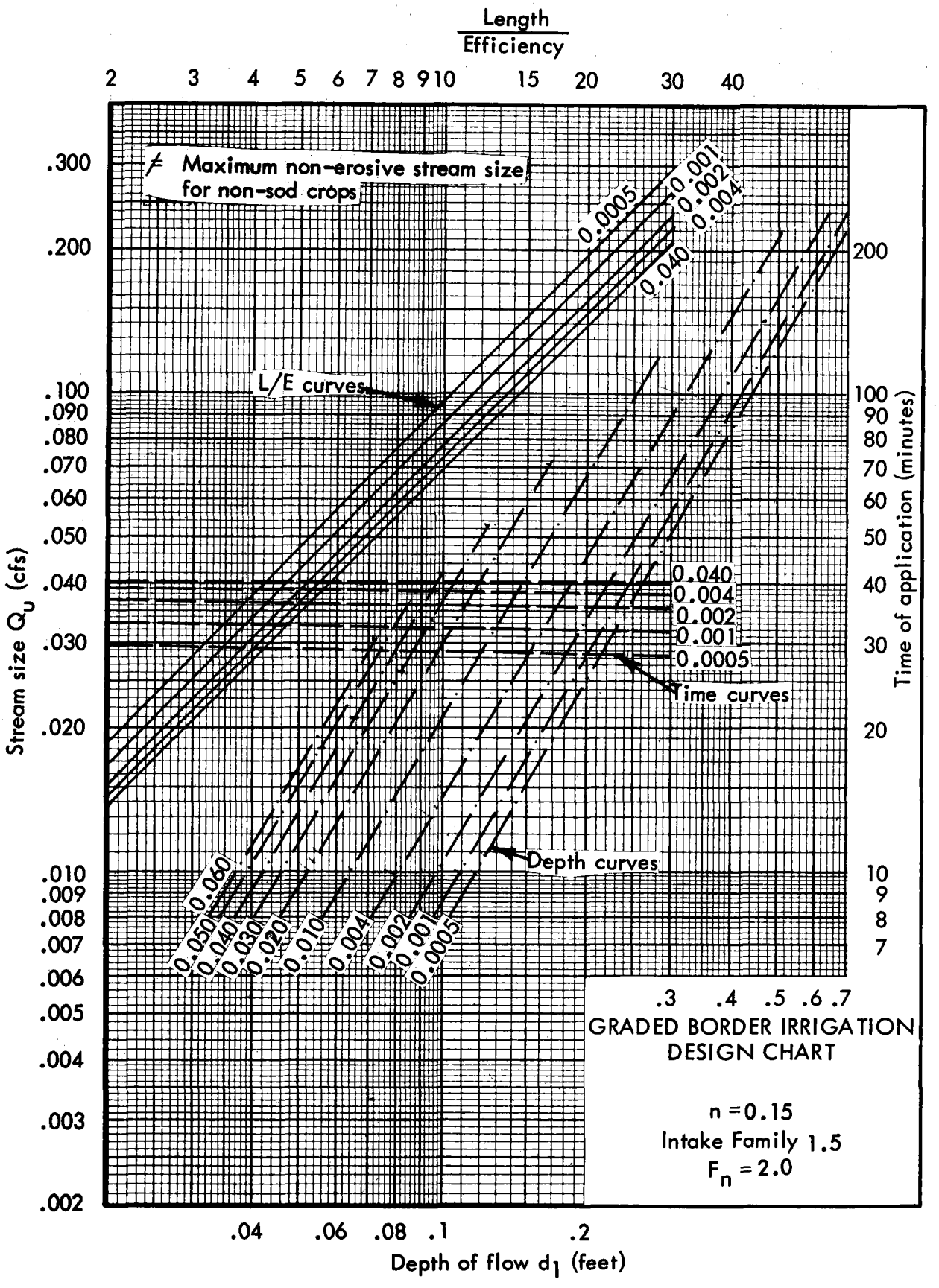

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
Time curves
Depth curves
0.0005
0.001
0.002
0.004
0.048
0.040
0.030
0.020
0.010
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
200 100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 2.0

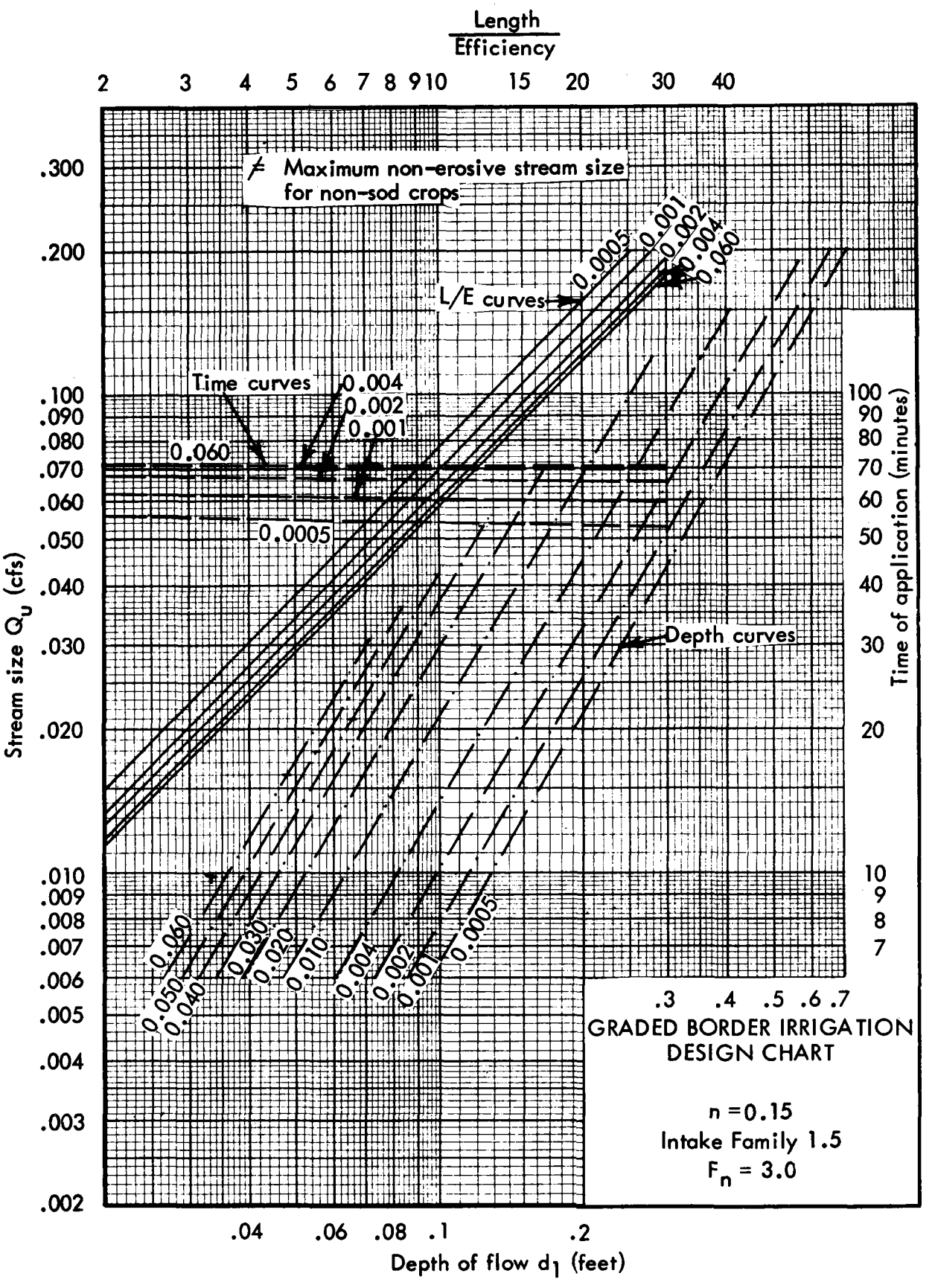

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non sod crops
0.002 0.004 0.001
0.034
0.0005
Time curves
L/E curves
0.0005
0.001
0.002
0.004
0.034
Depth curves
0.034
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

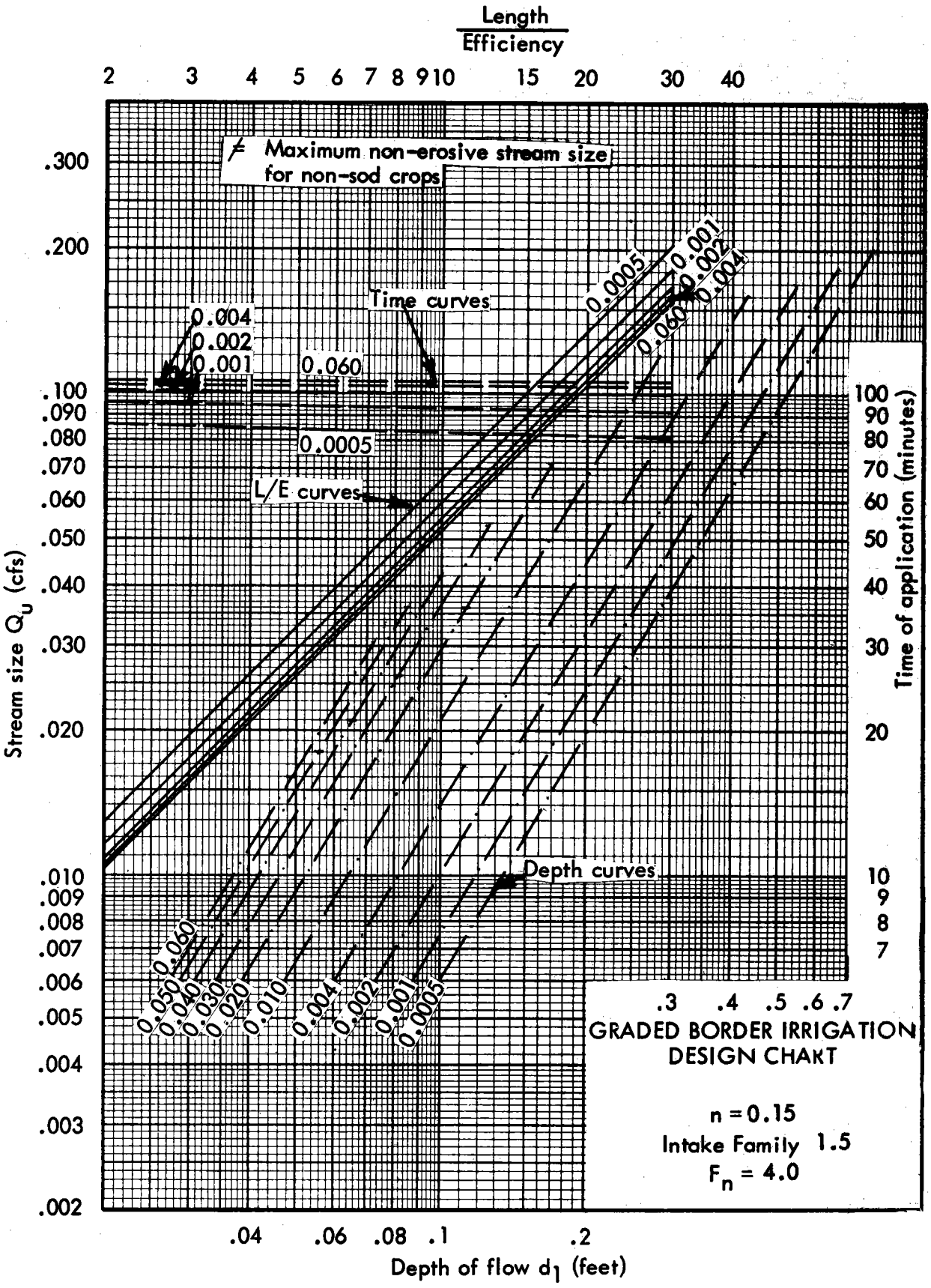

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.004
0.002
0.001
0.027
0.0005
Time curves
L/E curves
0.001
0.002
0.004
0.0005
0.027
Depth curves
0.027
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

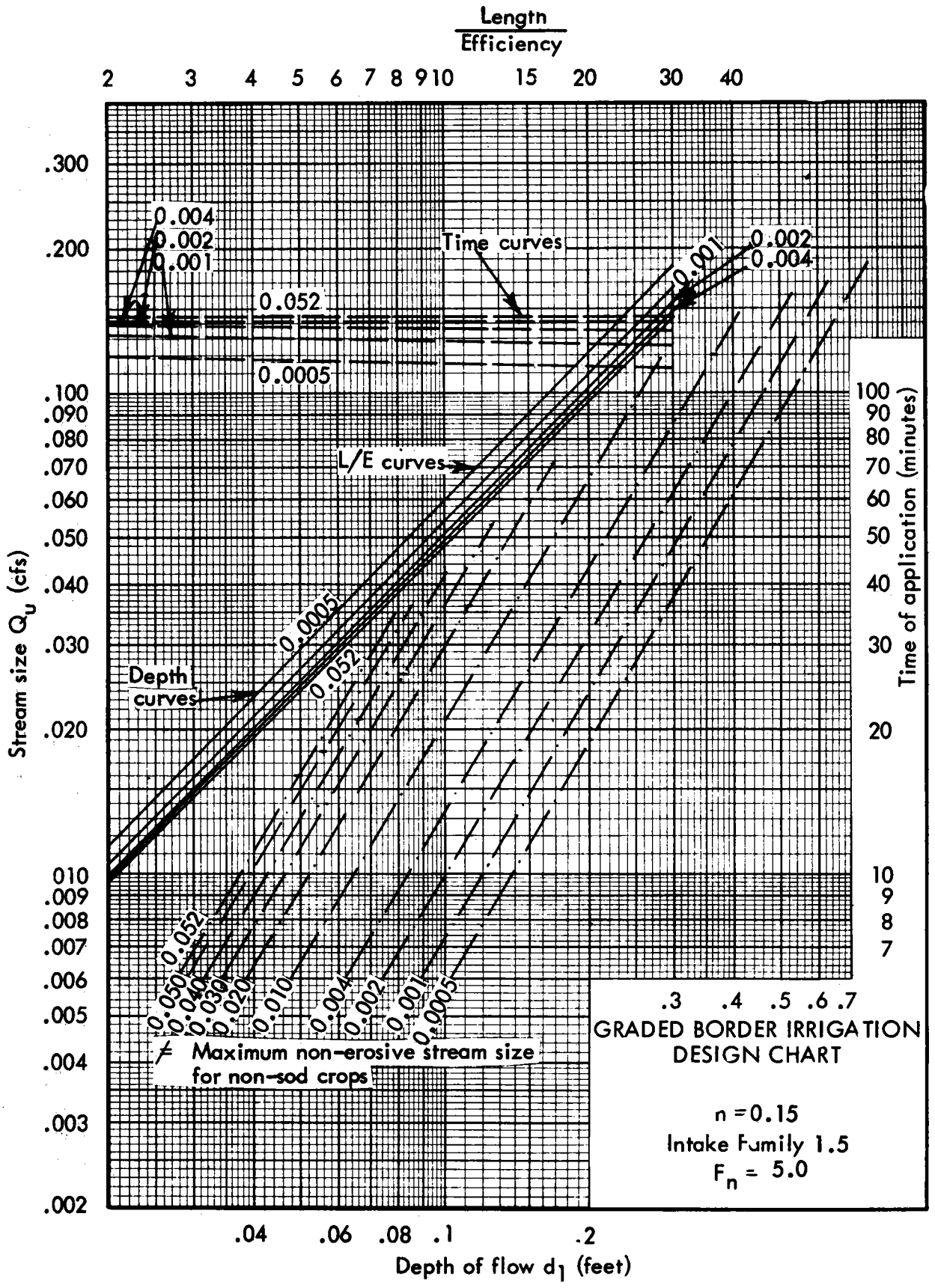

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.023
0.002
0.001
0.0005
Time curves
L/E curves
0.0005
0.023
0.001
0.002
Depth curves
0.023
0.020
0.010
0.004
0.002
0.001
0.004
≠ Maximum non-erosive stream size for non-sod crops
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

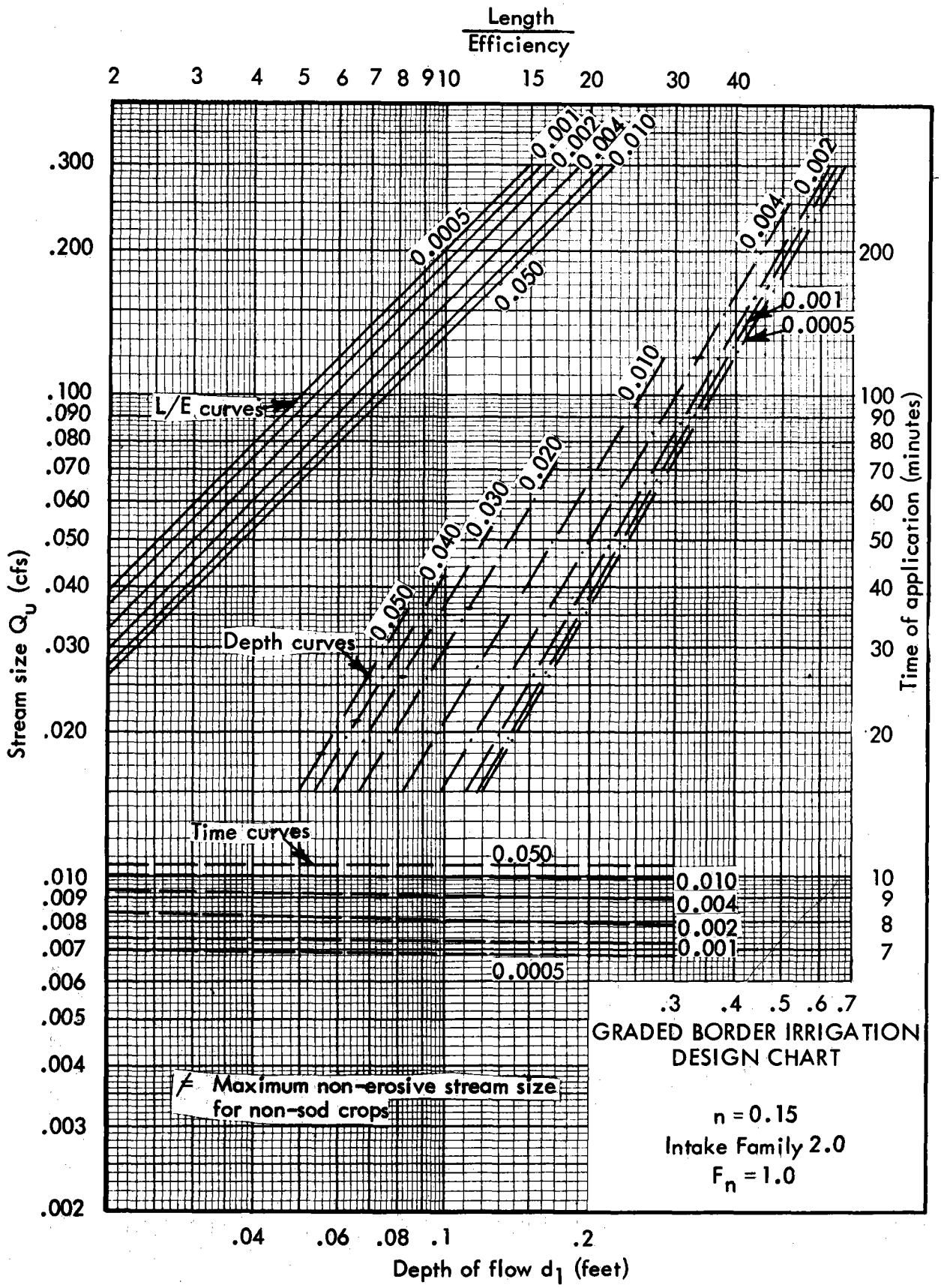

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.0005
0.001
0.002
0.004
0.010
0.040
L/E curves
0.060
0.050
0.040
0.030
0.020
0.010
Depth curves
Time curves
0.040
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

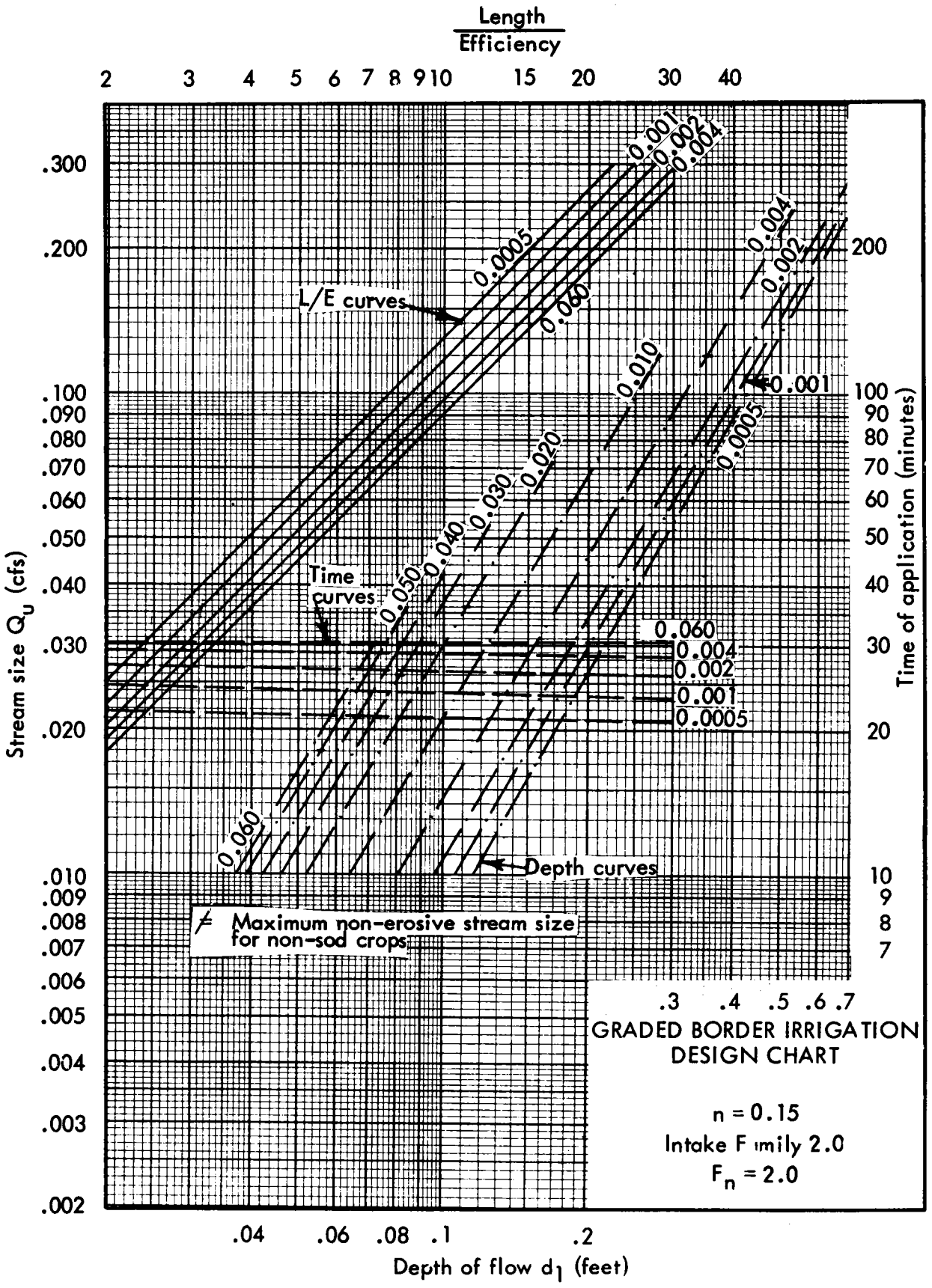

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Maximum non-erosive stream size for non-sod crops
0.0005
0.001
0.002
0.004
0.040
L/E curves
0.040
0.004
0.002
0.001
0.0005
Time curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

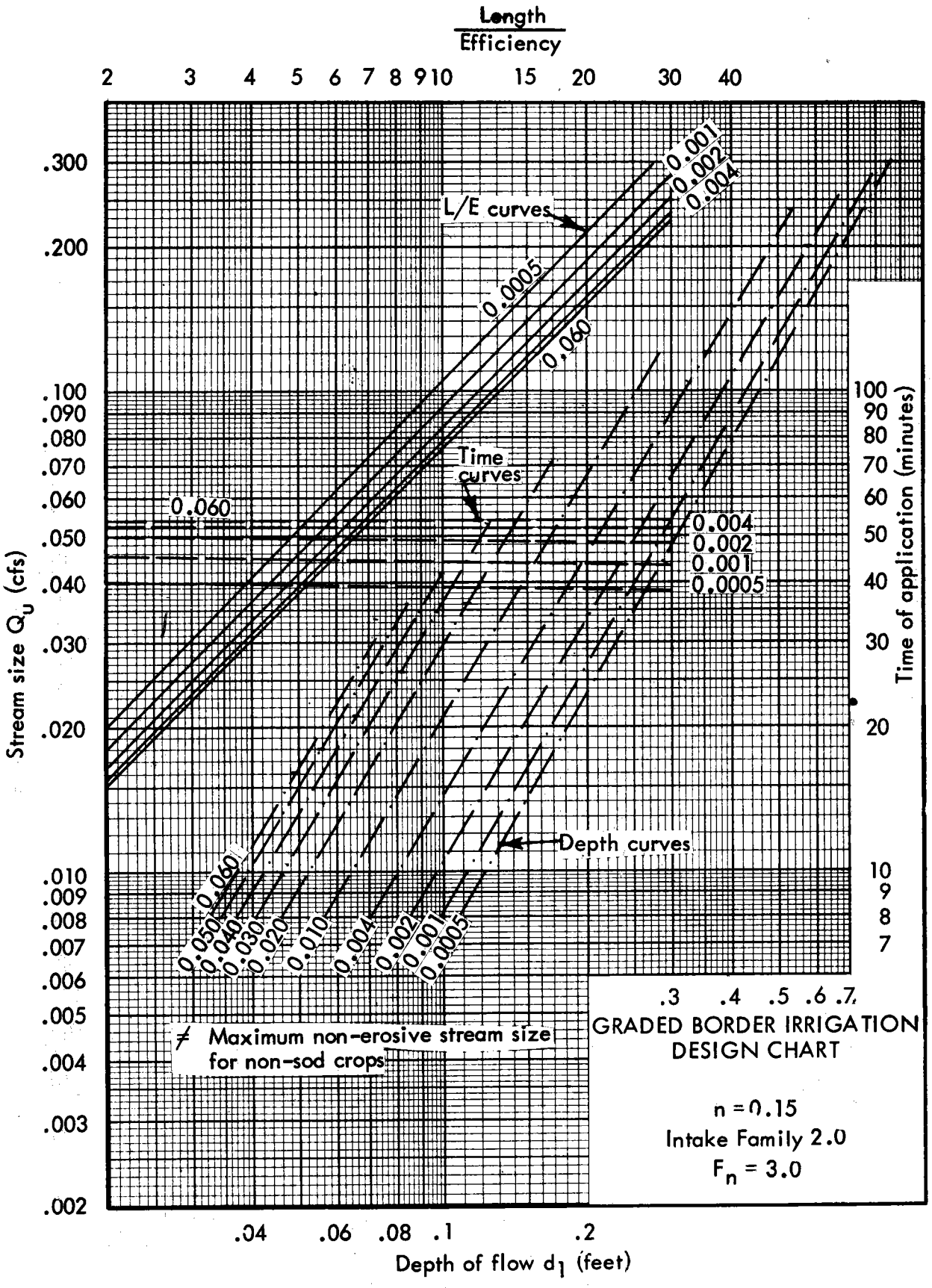

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
0.0005
0.001
0.002
0.004
0.060
Time curves
0.004
0.002
0.001
0.060
0.0005
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

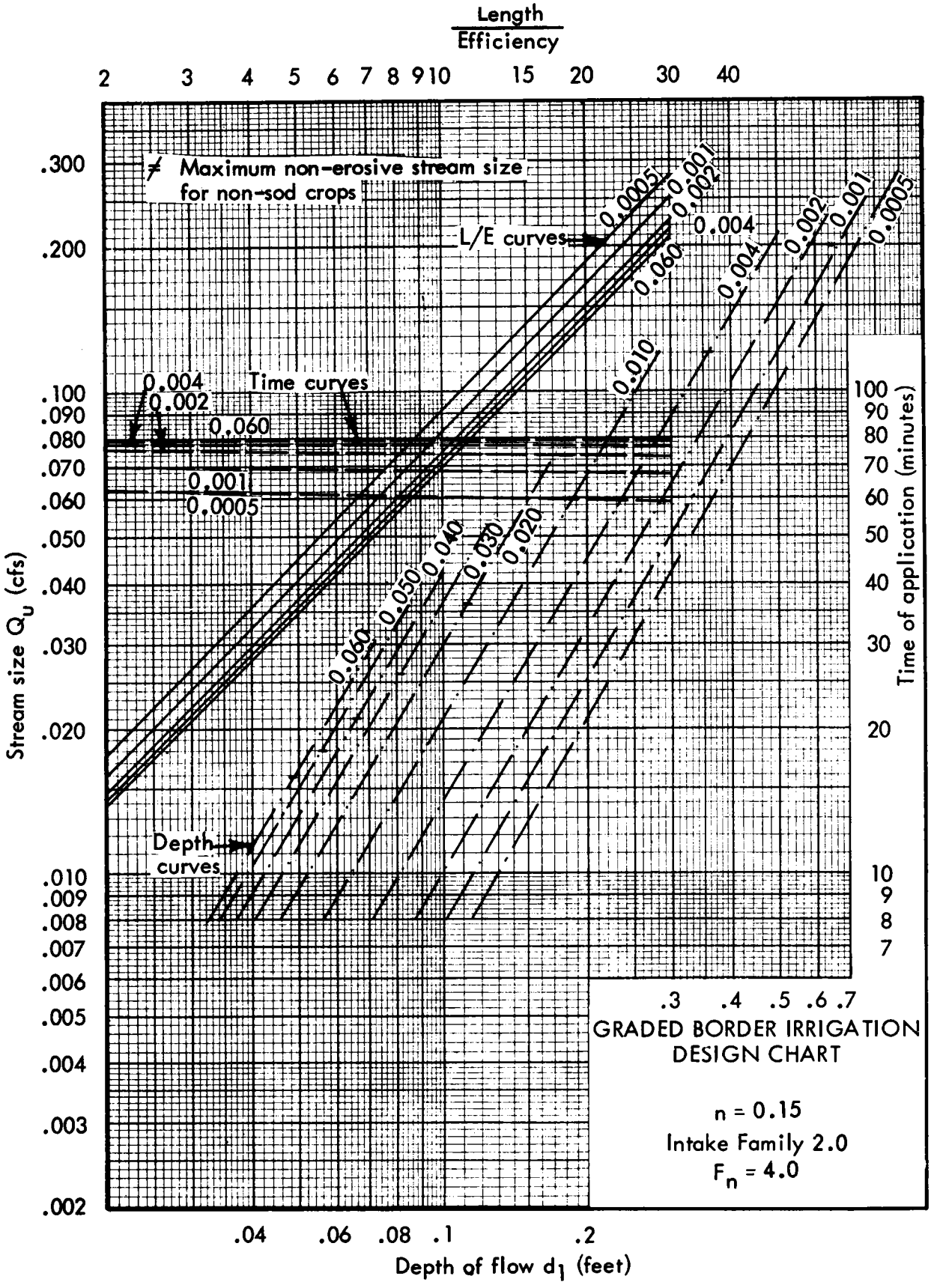

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.004
0.002
0.001
0.060
0.0005
L/E curves
0.0005
0.001
0.002
0.004
0.060
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

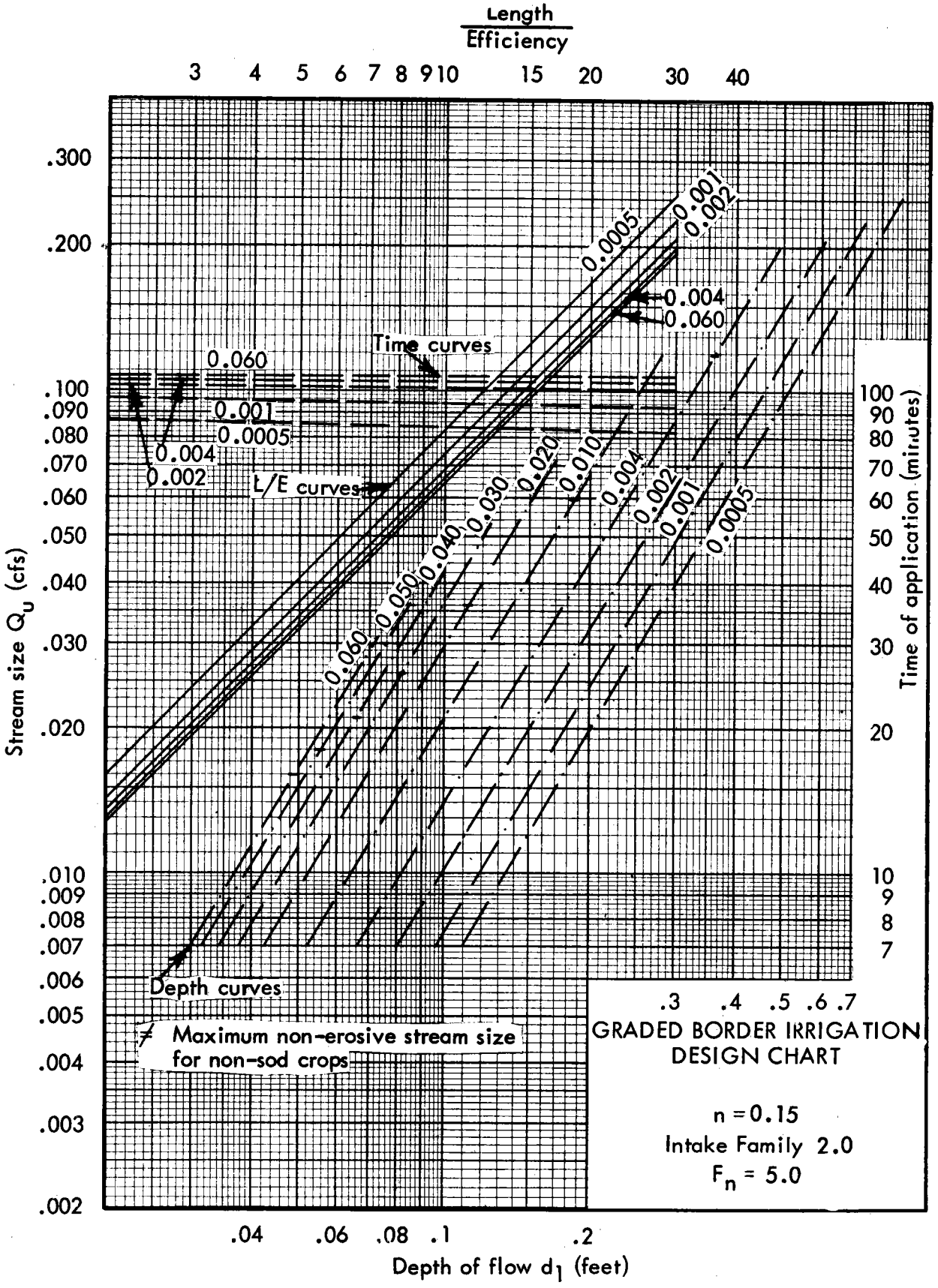

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.004
0.002
0.001
0.052
0.0005
Time curves
0.001
0.002
0.004
L/E curves
0.0005
0.052
Depth curves
0.050
0.052
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 1.5
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

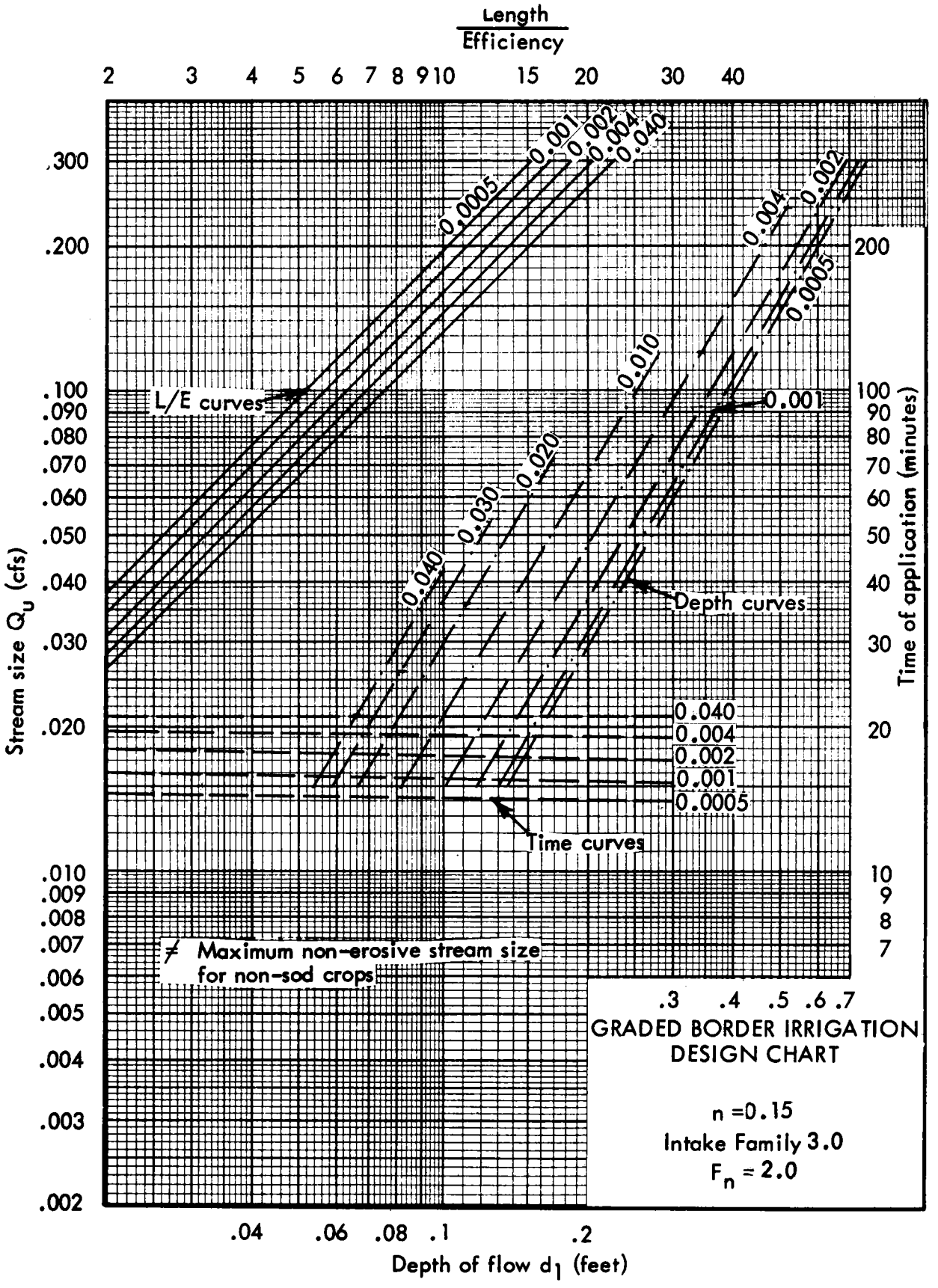

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
0.0005
0.001
0.002
0.004
0.010
0.050
L/E curves
0.020
0.030
0.040
Depth curves
Time curves
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 1.0
Maximum non-erosive stream size for non-sod crops
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

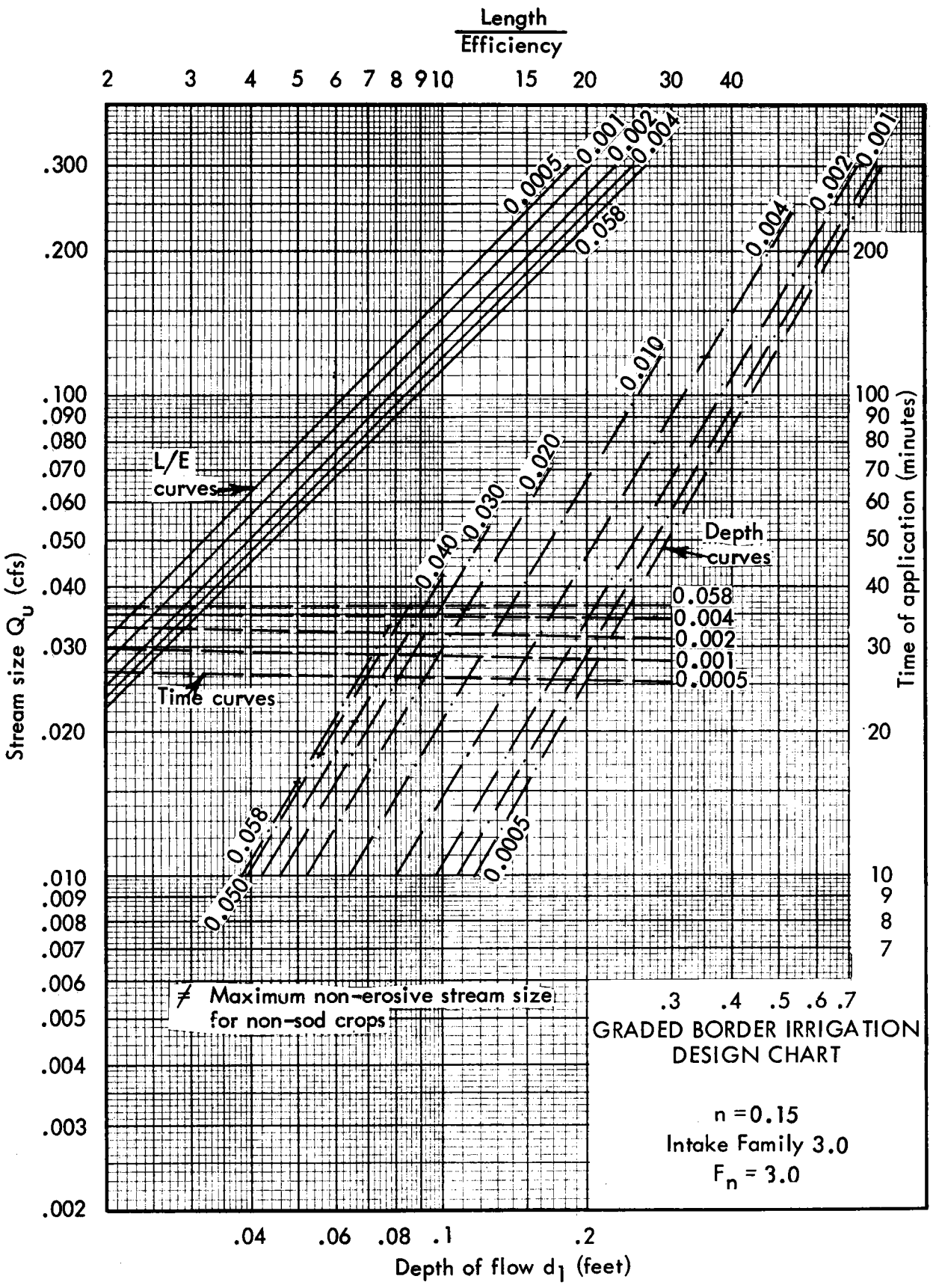

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
L/E curves
0.0005
0.001
0.002
0.004
0.060
0.010
0.020
0.030
0.040
0.050
Time curves
0.060
0.004
0.002
0.001
0.0005
Depth curves
Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

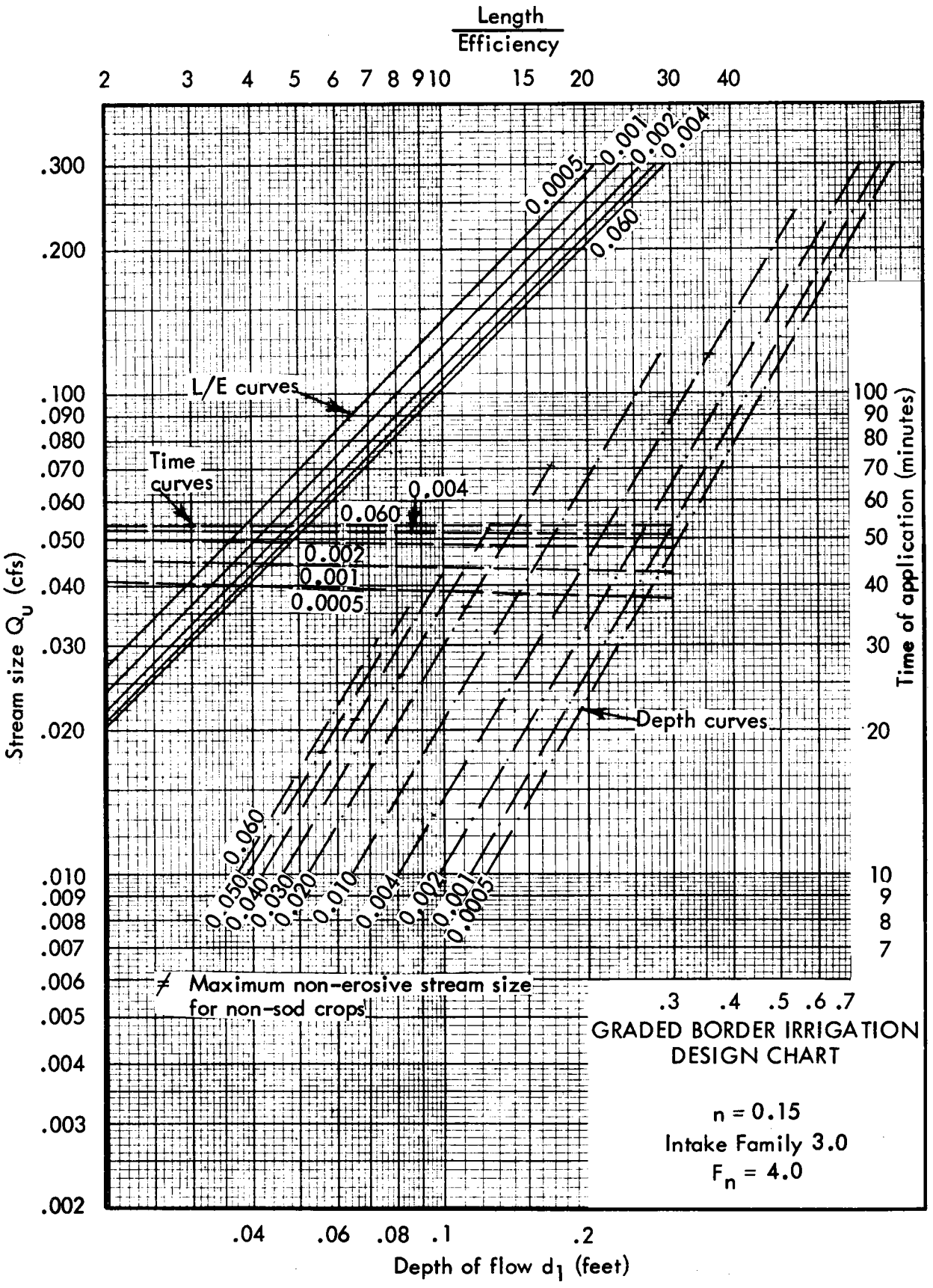

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
L/E curves
0.001
0.002
0.004
0.0005
0.060
Time curves
0.060
0.004
0.002
0.001
0.0005
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

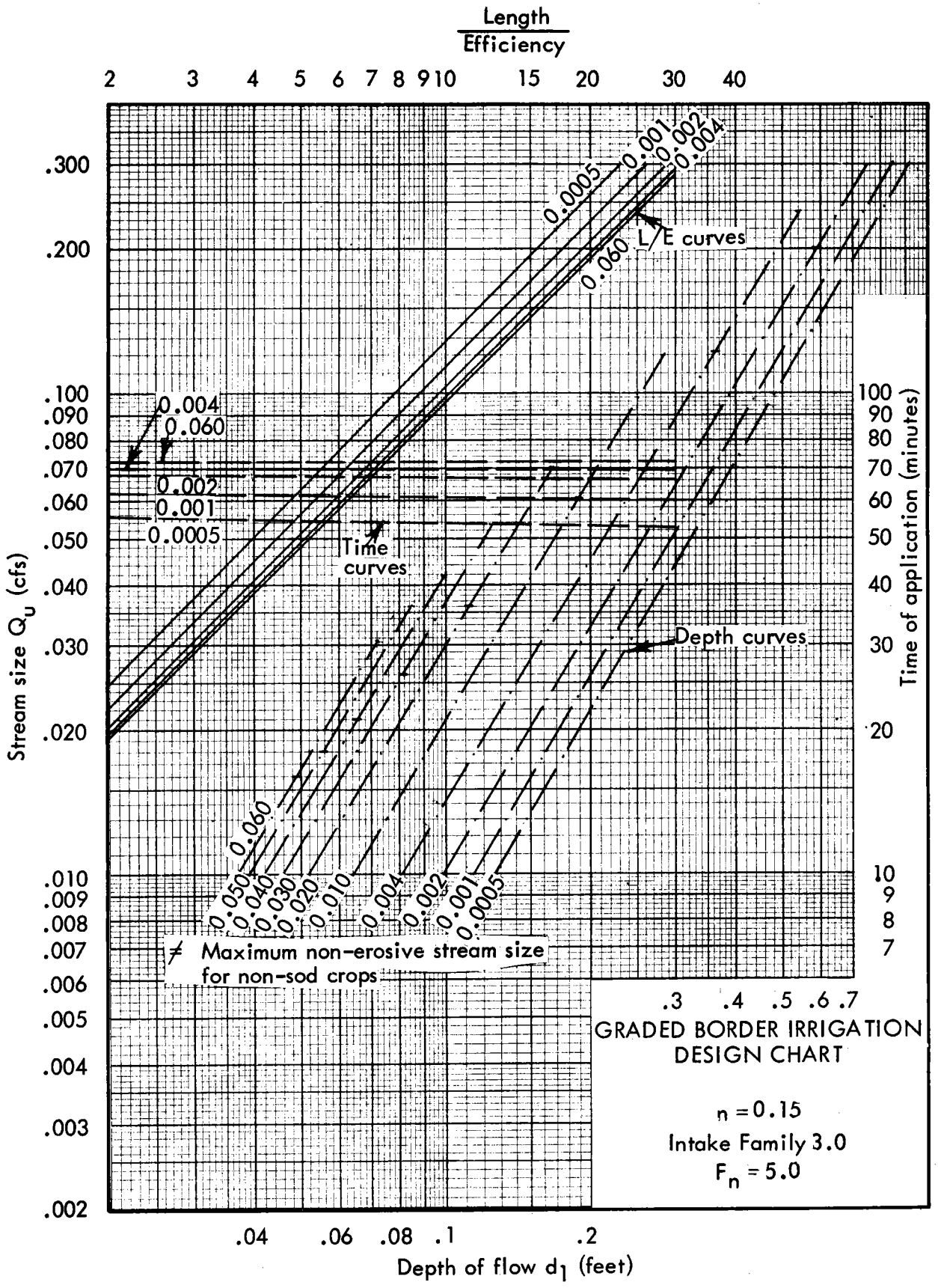

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
L/E curves
0.0005
0.001
0.002
0.004
0.060
0.010
Time curves
0.004
0.002
0.060
0.001
0.0005
0.050
0.040
0.030
0.020
Depth curves
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

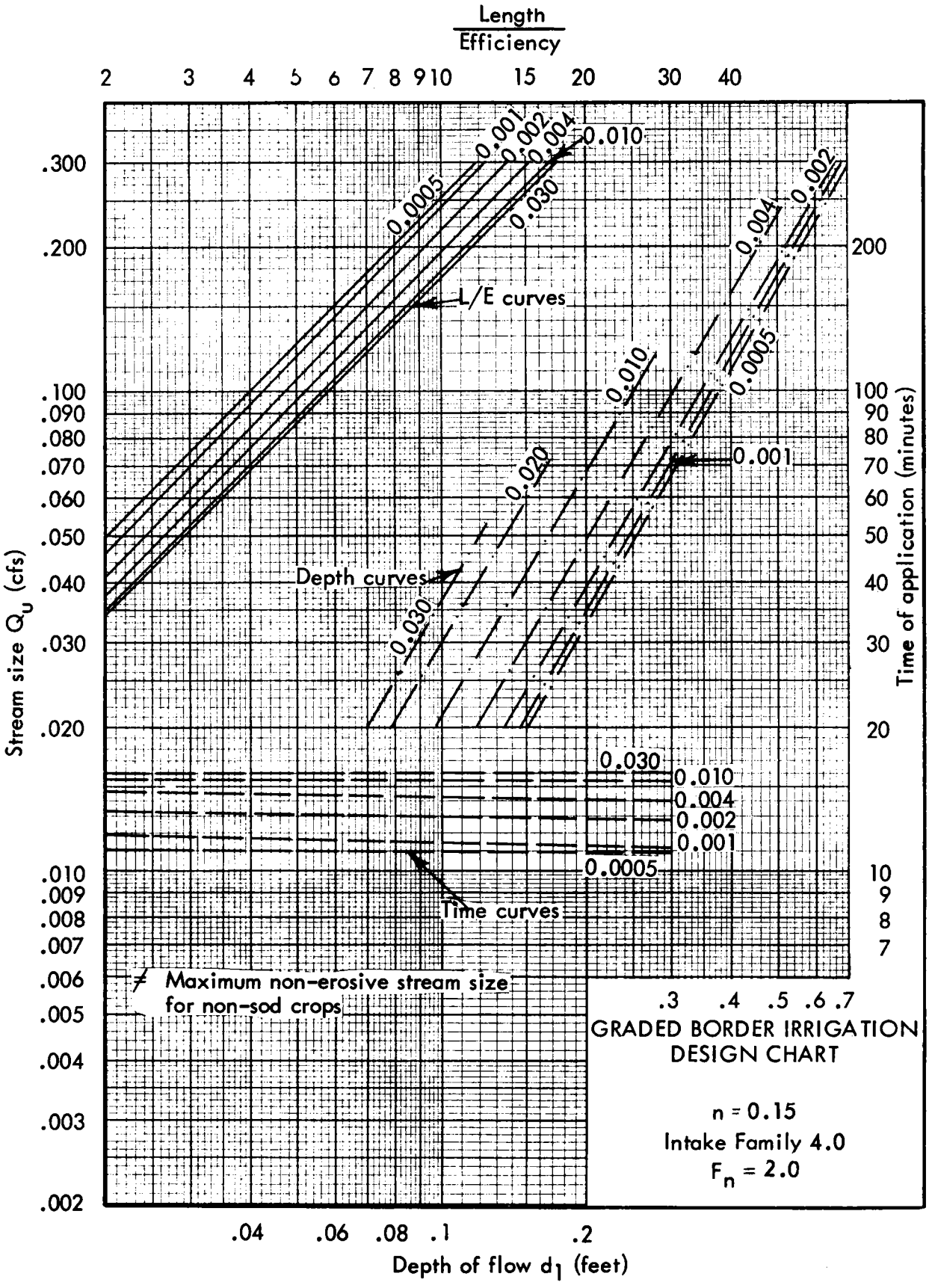

Length / Efficiency
3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
Time of application (minutes)
100 90 80 70 60 50 40 30 20 10 9 8 7
Time curves
L/E curves
Depth curves
0.060
0.001
0.0005
0.004
0.002
0.0005
0.001
0.002
0.004
0.060
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 2.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

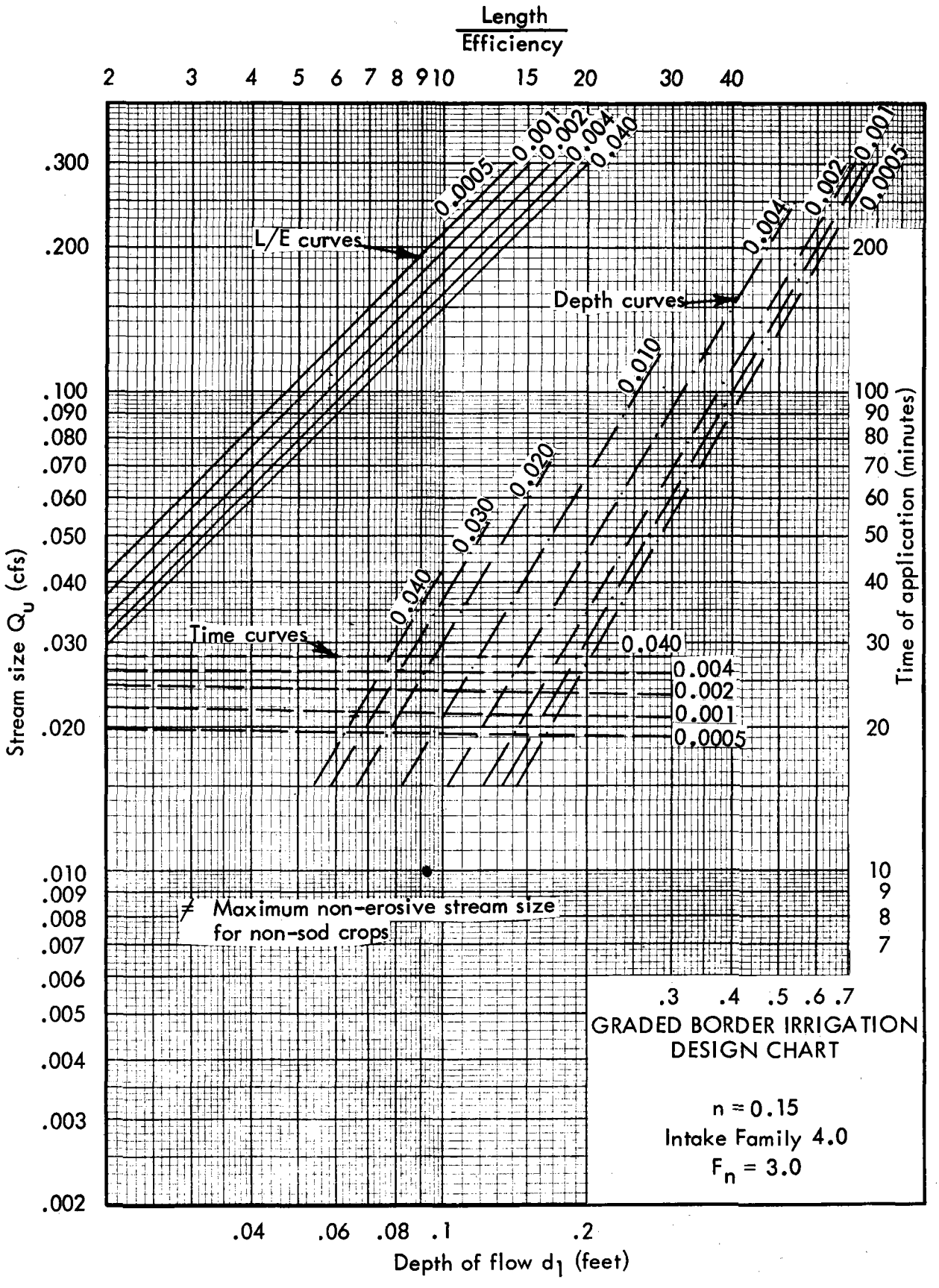

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
L/E curves
0.0005
0.001
0.002
0.004
0.040
0.010
0.020
0.030
0.040
0.001
0.004
0.002
0.0005
Depth curves
0.040
0.004
0.002
0.001
0.0005
Time curves
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

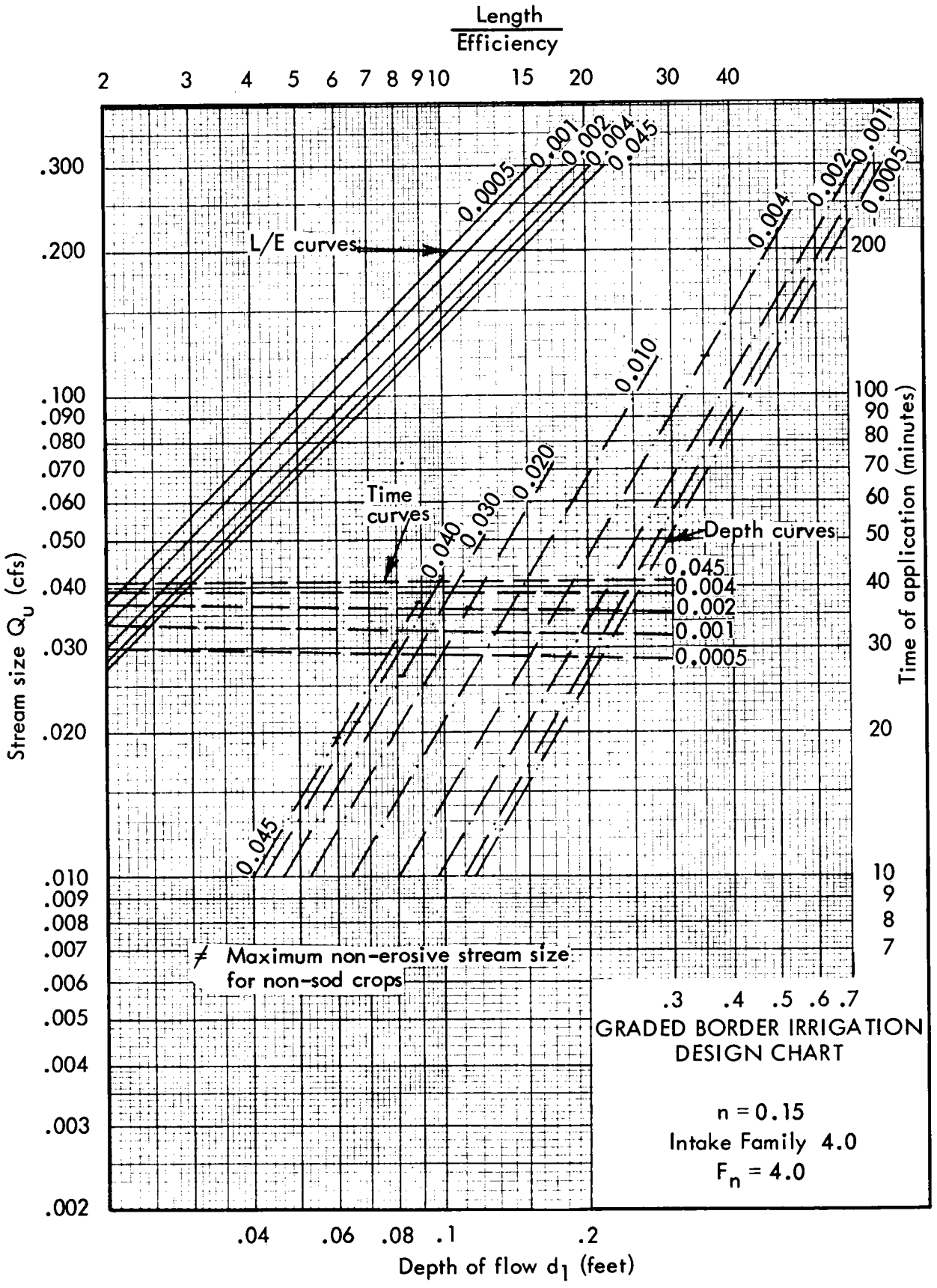

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
L/E curves
Time curves
Depth curves
0.0005
0.001
0.002
0.004
0.058
0.010
0.020
0.030
0.040
0.050
0.058
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 3.0

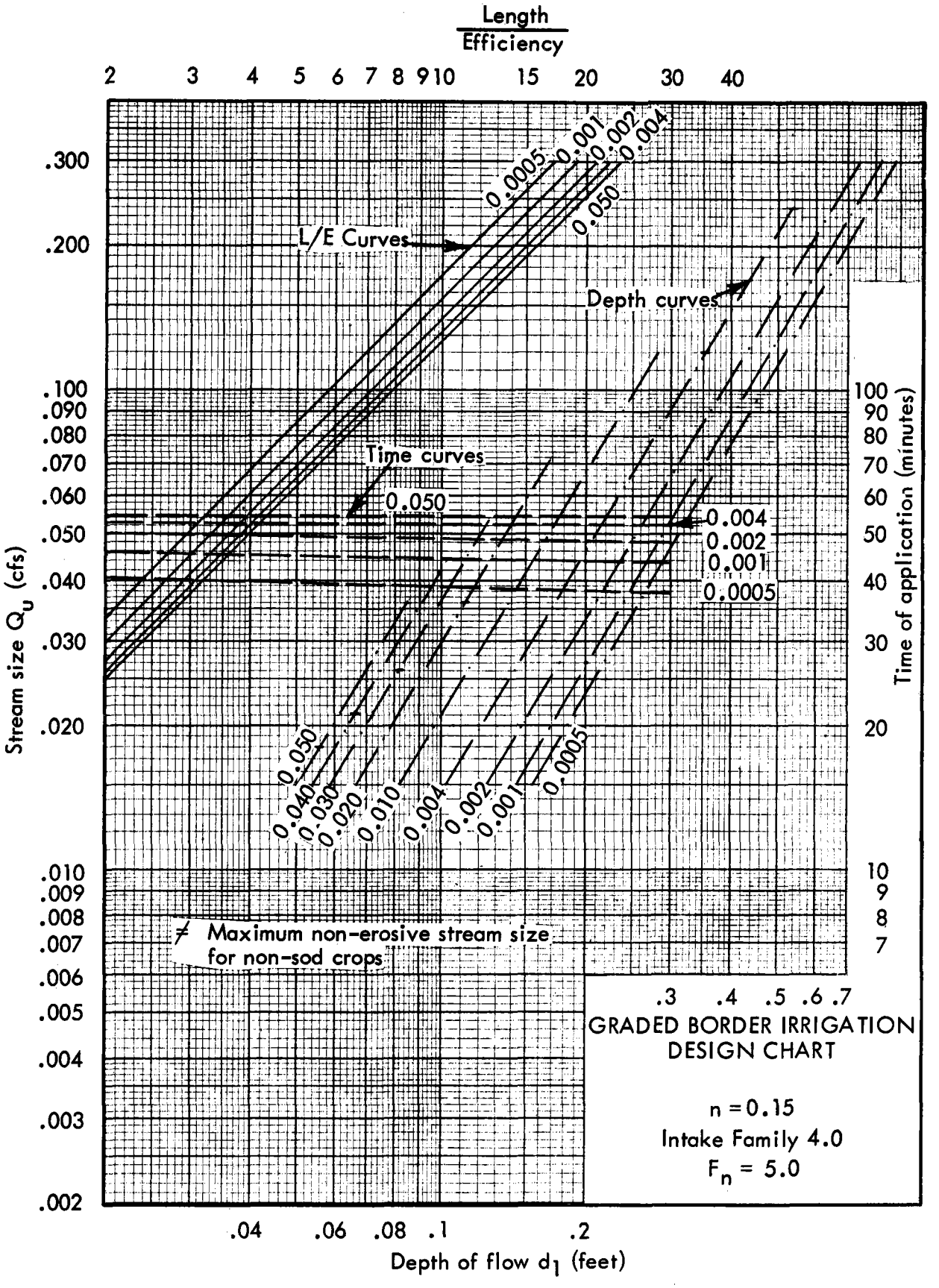

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
L/E curves
Time curves
Depth curves
0.0005
0.001
0.002
0.004
0.060
0.050
0.040
0.030
0.020
0.010
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

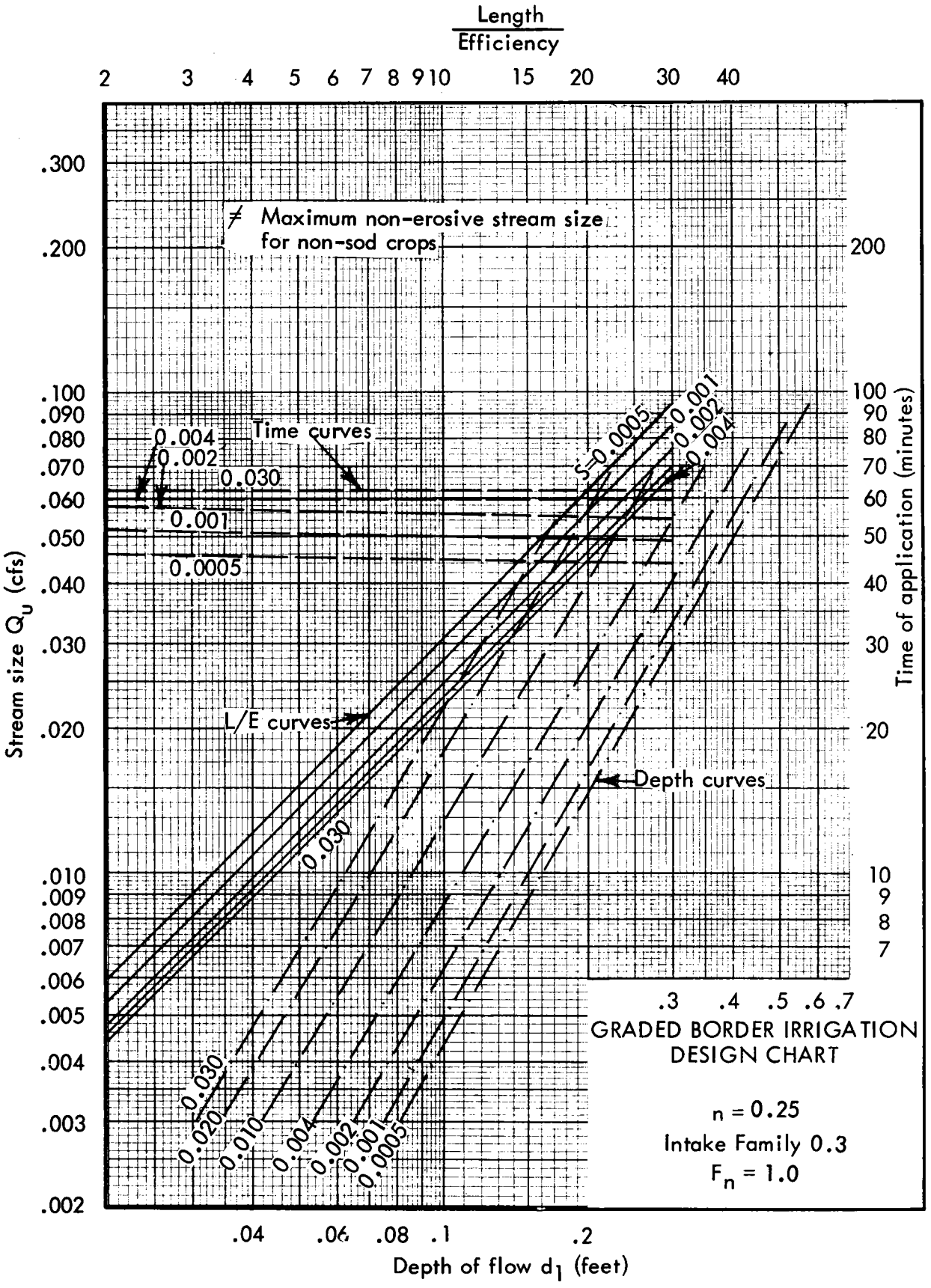

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.0005
0.001
0.002
0.004
0.060
L/E curves
0.004
0.060
0.002
0.001
0.0005
Time curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 3.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

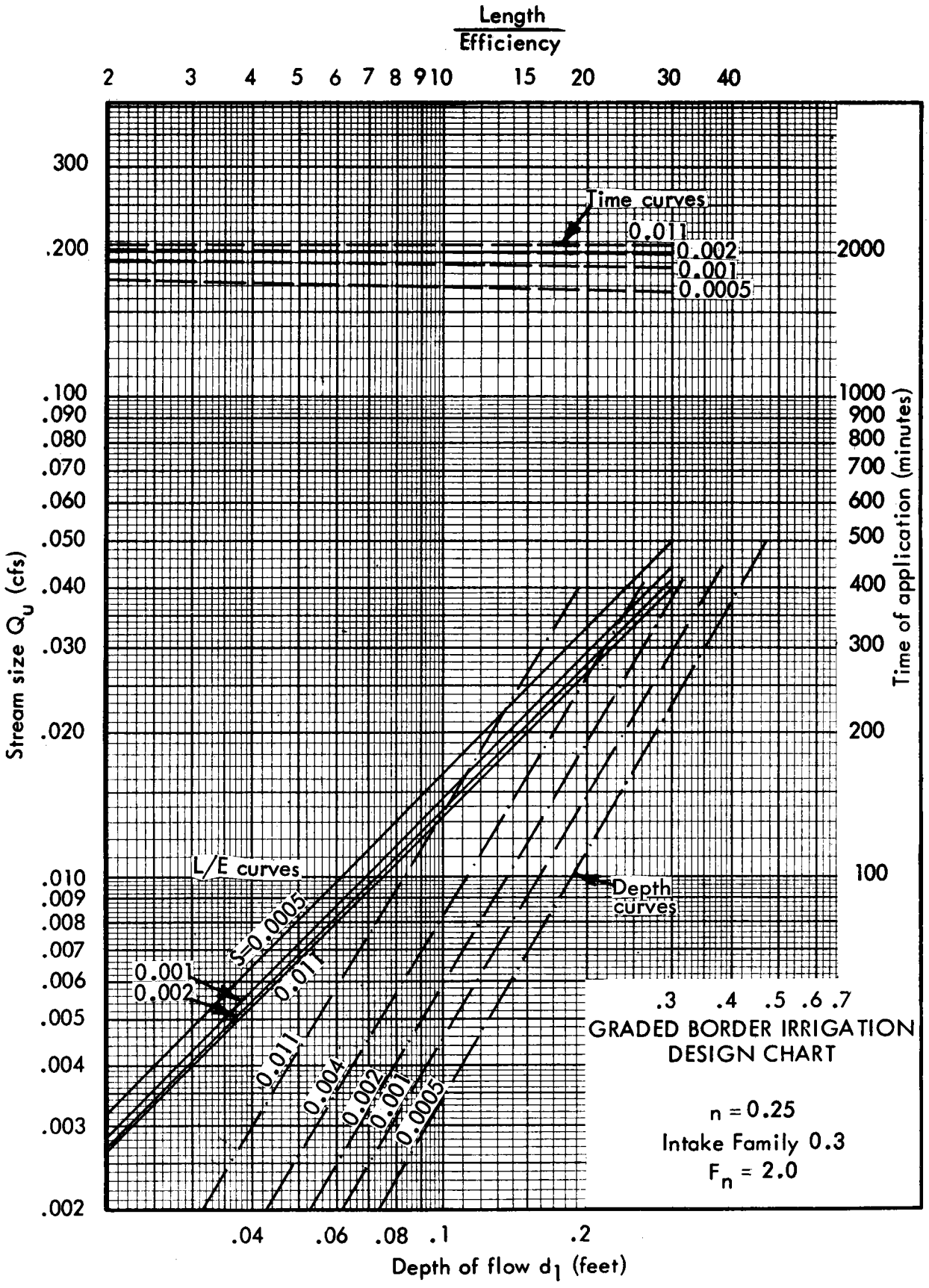

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
0.0005
0.001
0.002
0.004
0.010
0.030
L/E curves
0.002
0.004
0.0005
0.010
0.001
0.020
Depth curves
0.030
0.030
0.010
0.004
0.002
0.001
0.0005
Time curves
≠ Maximum non-erosive stream size for non-sod crops
200
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

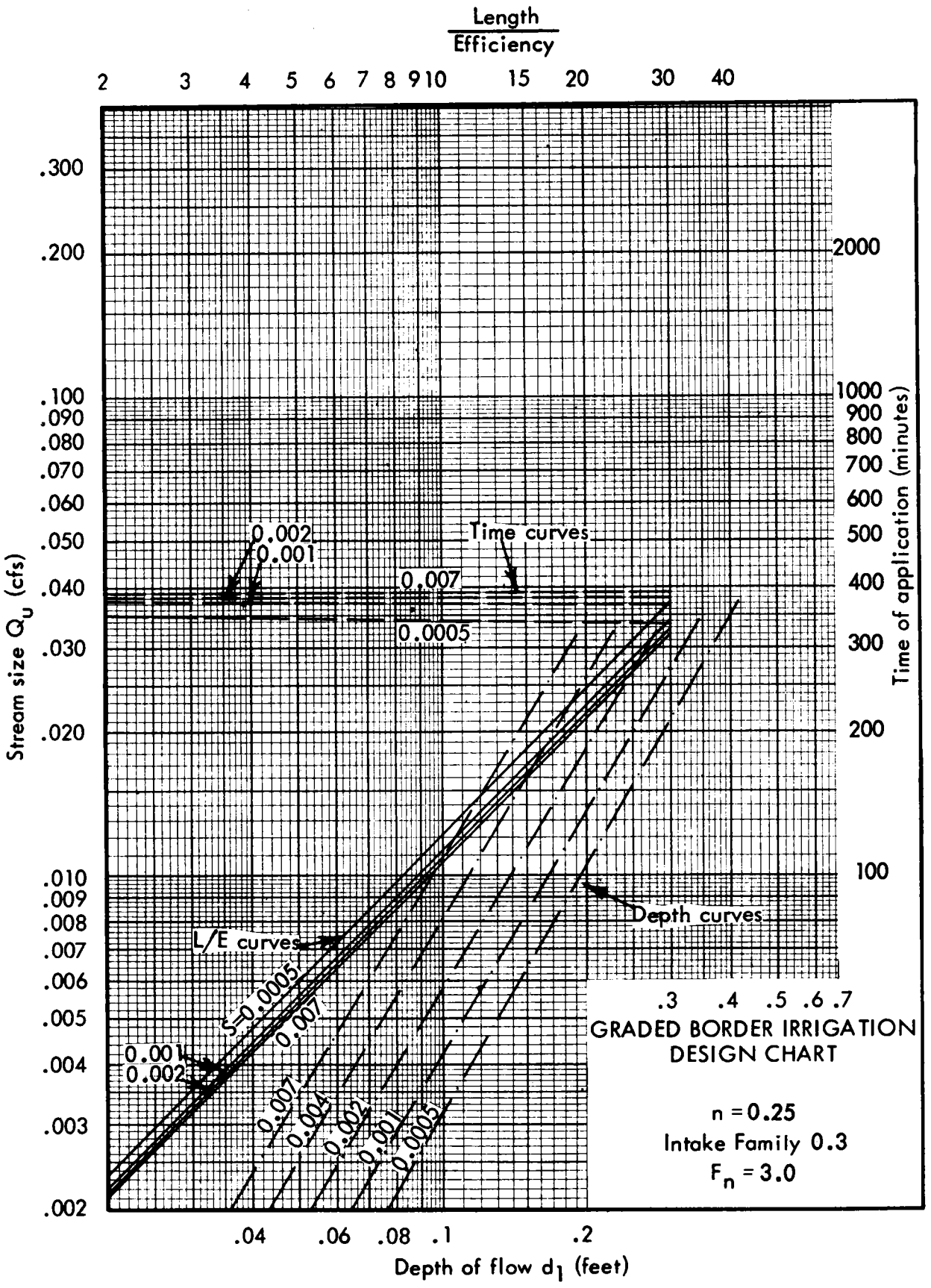

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
L/E curves
0.0005
0.001
0.002
0.004
0.040
Depth curves
0.010
0.020
0.030
0.040
0.004
0.002
0.001
0.0005
Time curves
0.040
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

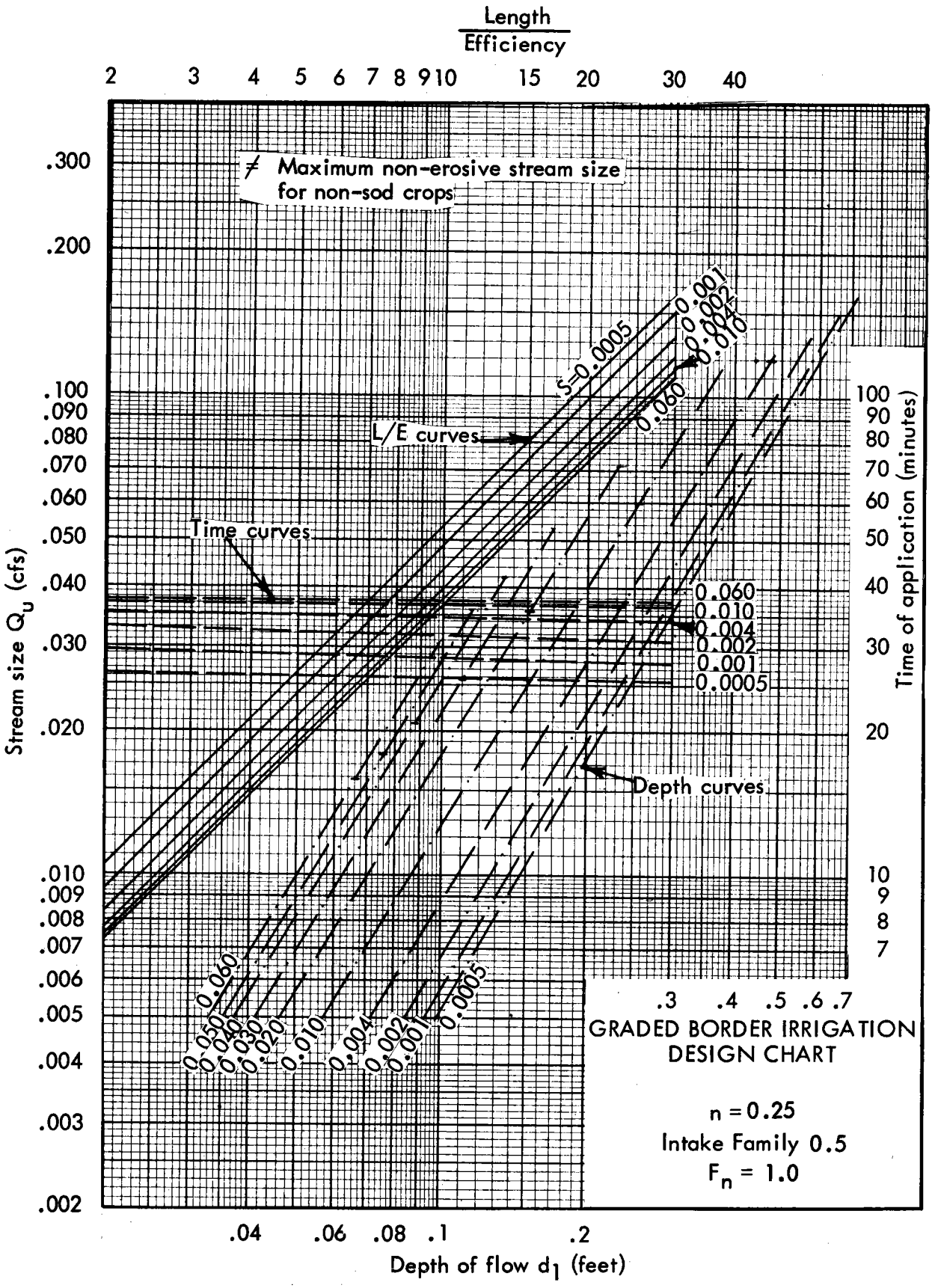

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
L/E curves
0.0005
0.001
0.002
0.004
0.045
Time curves
0.010
0.020
0.030
0.040
0.045
Depth curves
0.045
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

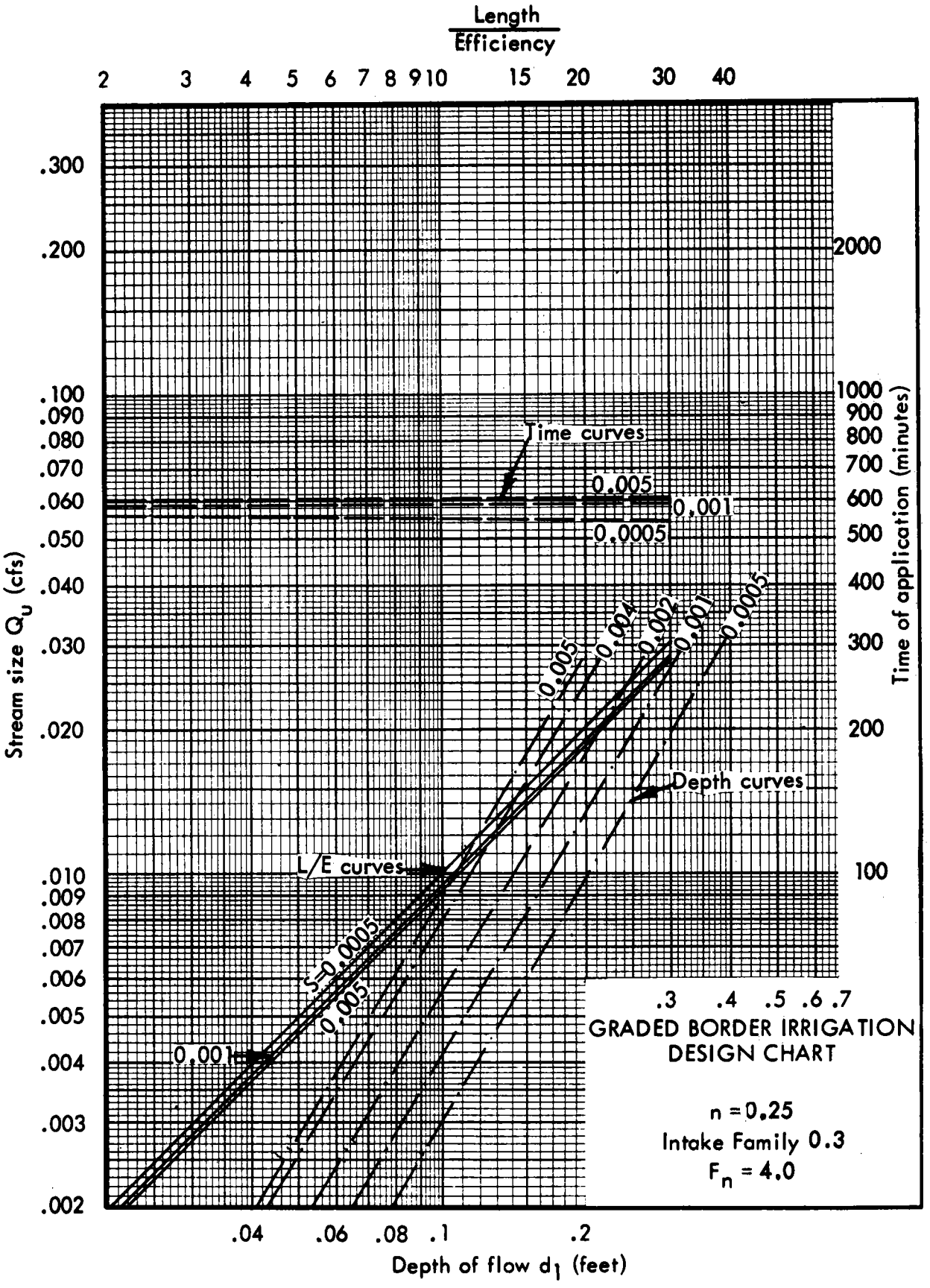

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
L/E Curves
0.0005
0.001
0.002
0.004
0.050
Depth curves
Time curves
0.050
0.004
0.002
0.001
0.0005
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.15
Intake Family 4.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

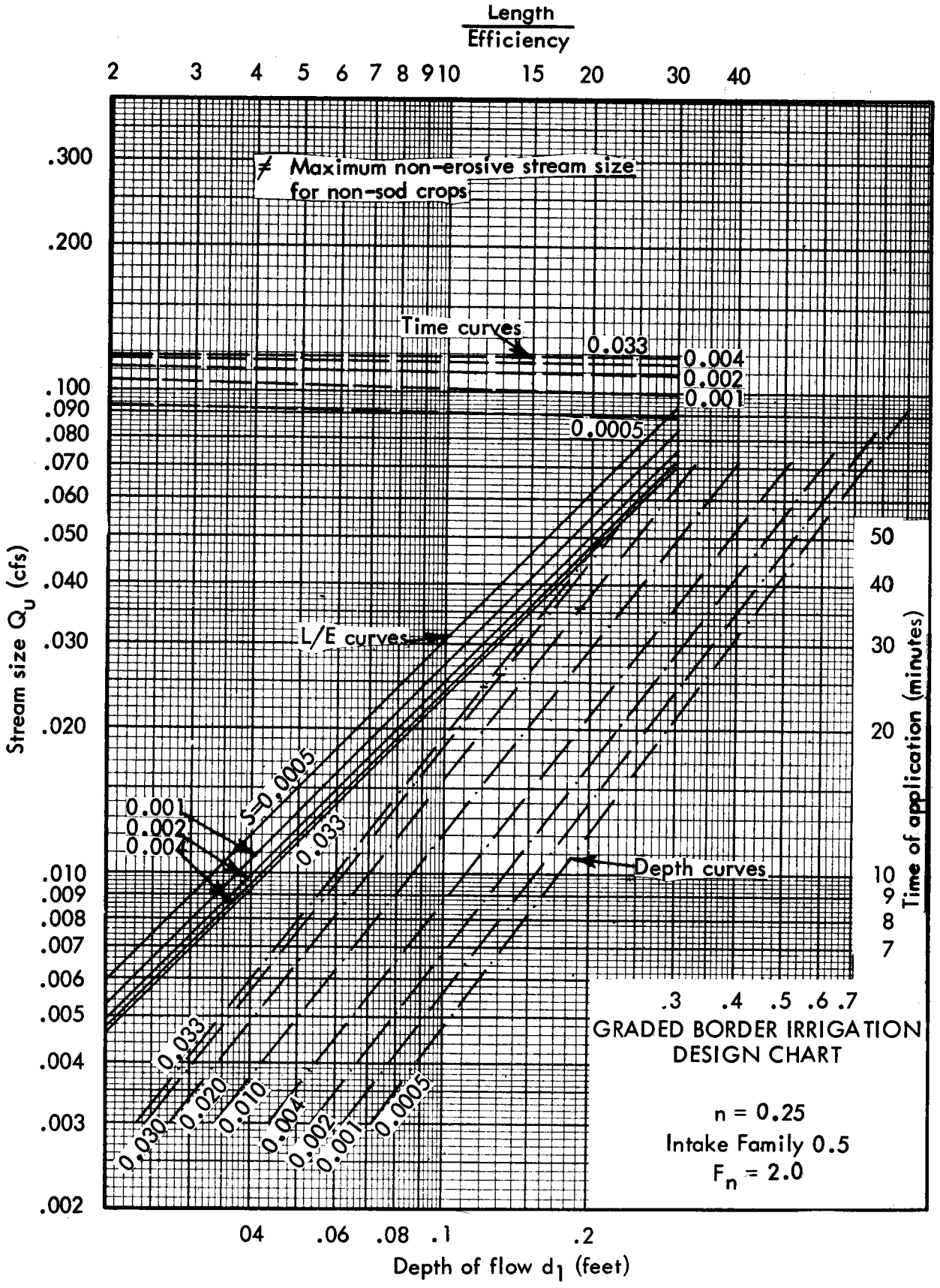

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.004
0.002
0.030
0.001
0.0005
S=0.0005
0.001
0.002
0.004
L/E curves
Depth curves
0.030
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

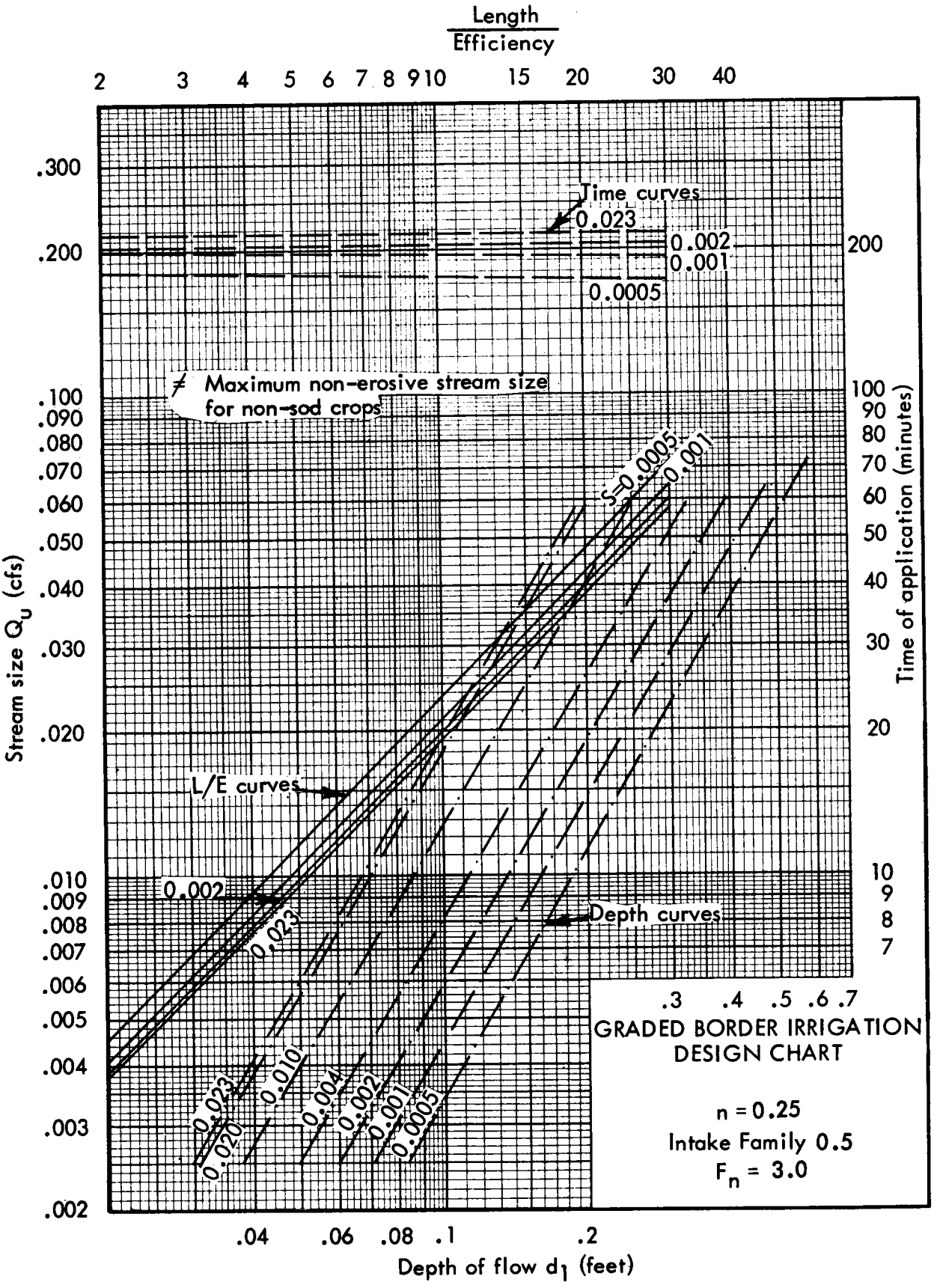

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.011
0.002
0.001
0.0005
L/E curves
S=0.0005
0.001
0.002
0.01
0.011
0.004
0.002
0.001
0.0005
Depth curves
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 2.0
Stream size Q_u (cfs)
Time of application (minutes)
Depth of flow d_1 (feet)

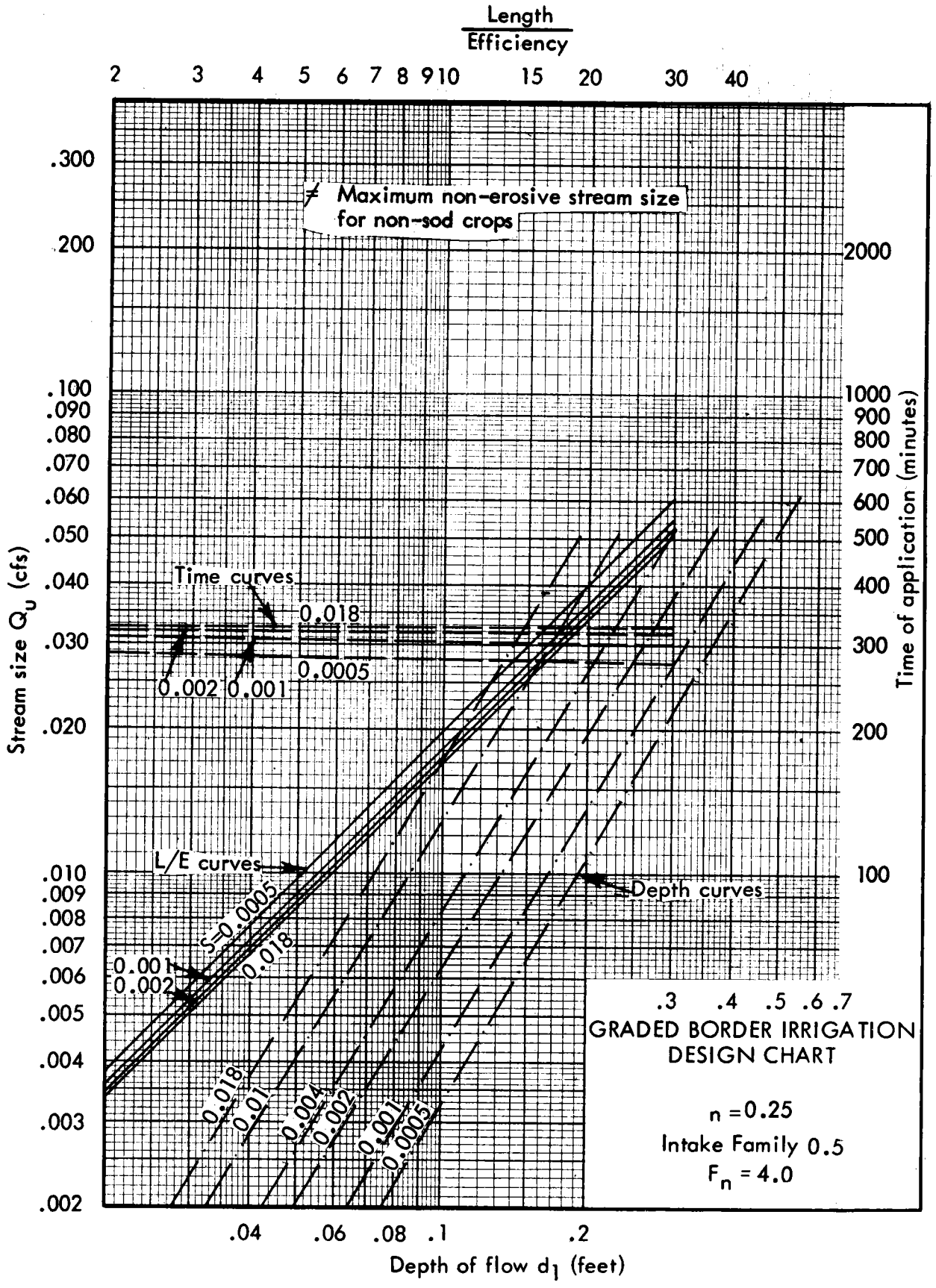

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
0.002
0.001
0.007
0.0005
Time curves
Depth curves
L/E curves
S=0.0005
0.007
0.001
0.002
0.007
0.004
0.002
0.001
0.0005
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 3.0

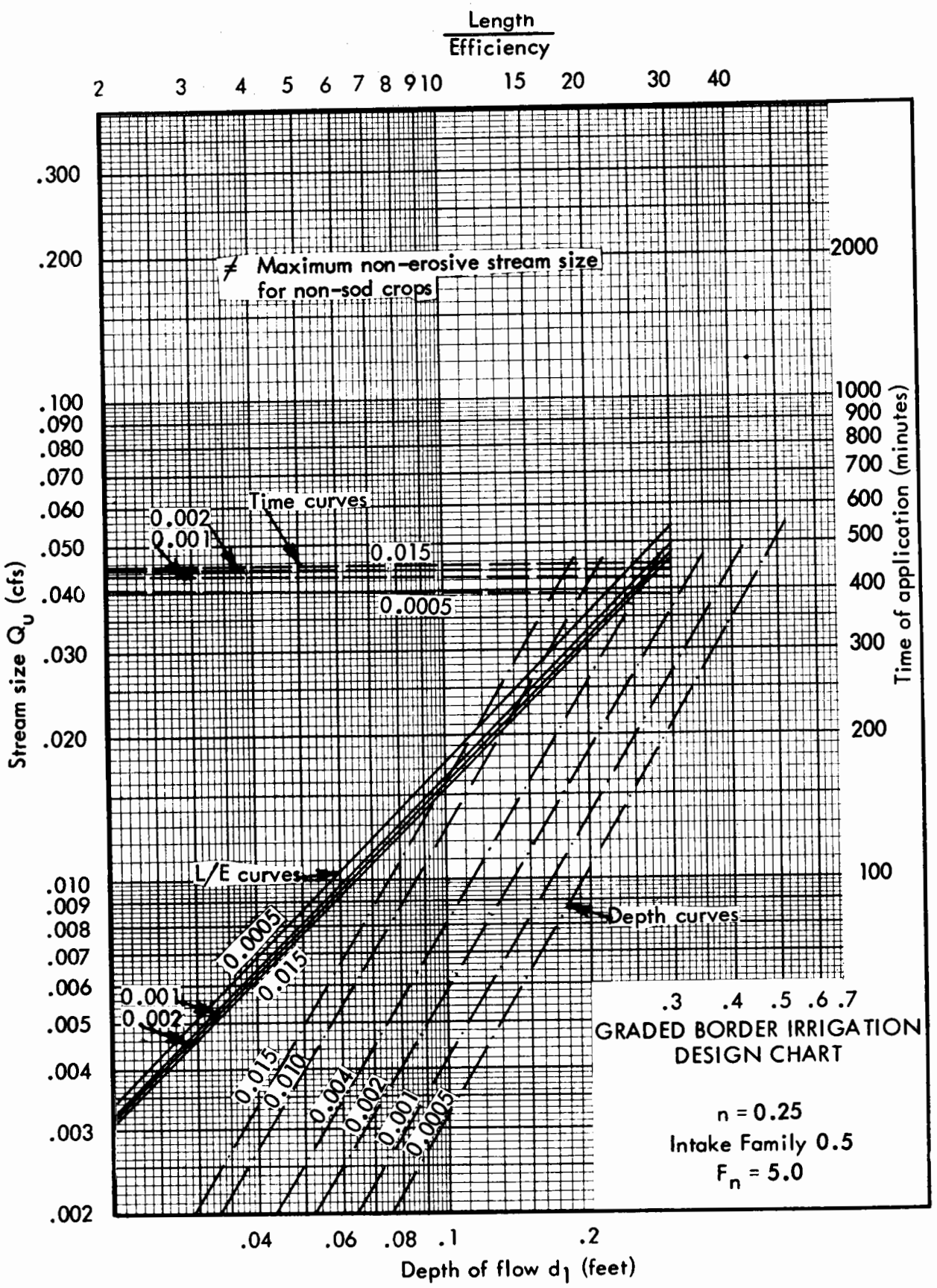

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
S=0.0005
0.001
0.002
0.004
0.010
0.060
L/E curves
Time curves
Depth curves
0.060
0.010
0.004
0.002
0.001
0.0005
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

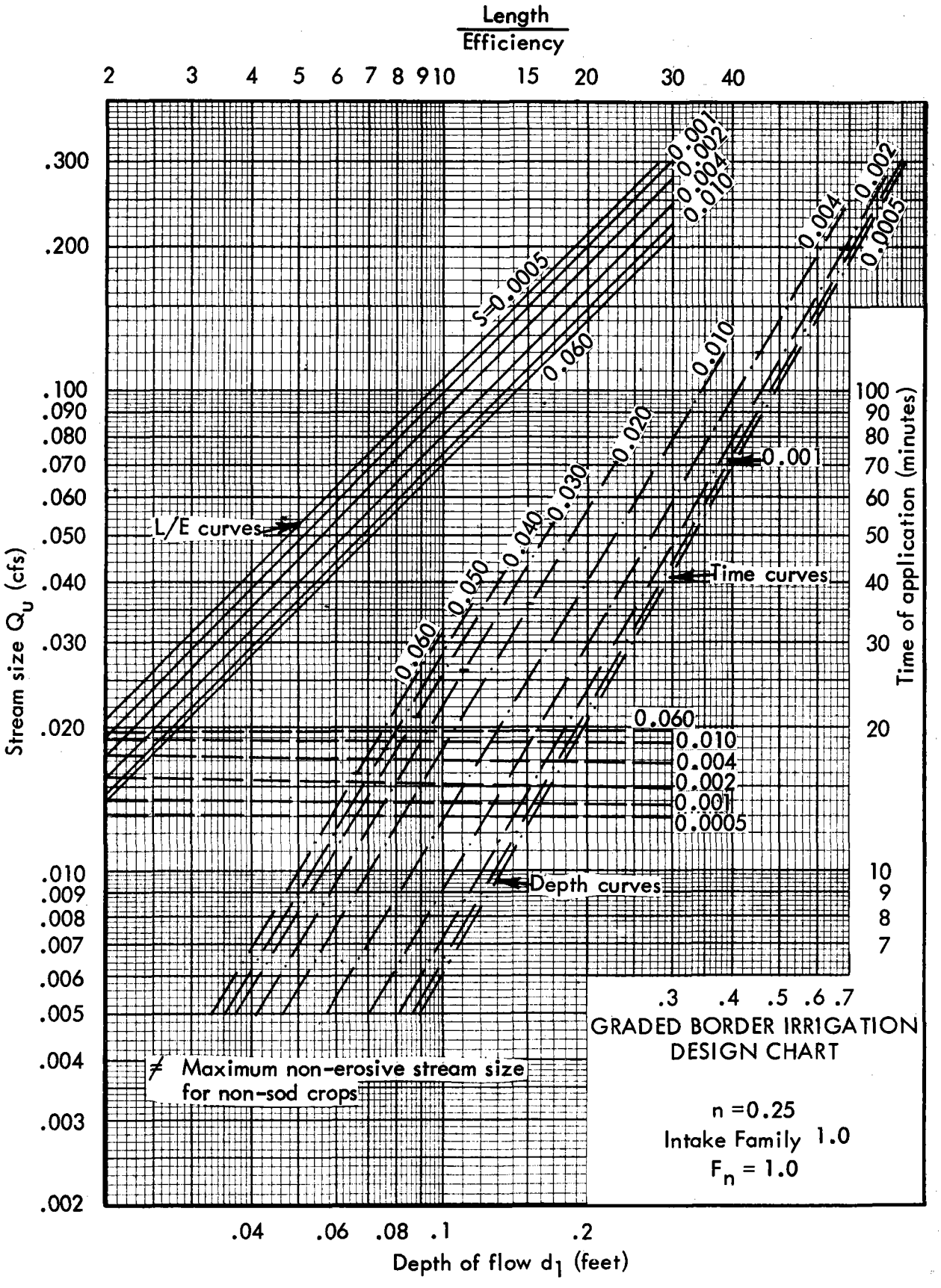

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
Time curves
0.005
0.001
0.0005
0.005
0.004
0.002
0.001
0.0005
Depth curves
L/E curves
S=0.0005
0.005
0.001
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n = 0.25
Intake Family 0.3
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

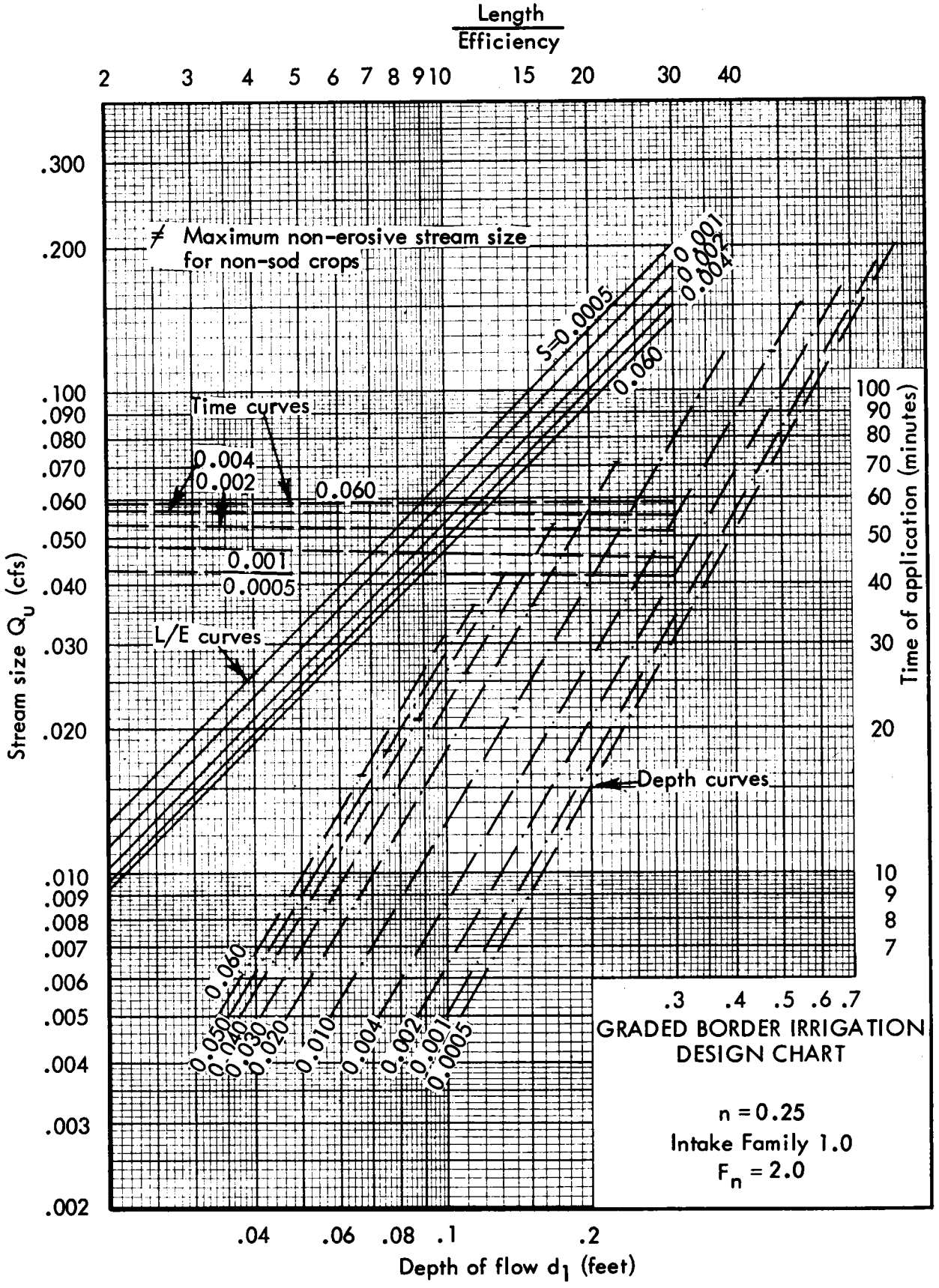

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.033
0.004
0.002
0.001
0.0005
L/E curves
S=0.0005
0.001
0.002
0.004
0.033
Depth curves
0.033
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 2.0
04 .06 .08 .1 .2
Depth of flow d_1 (feet)

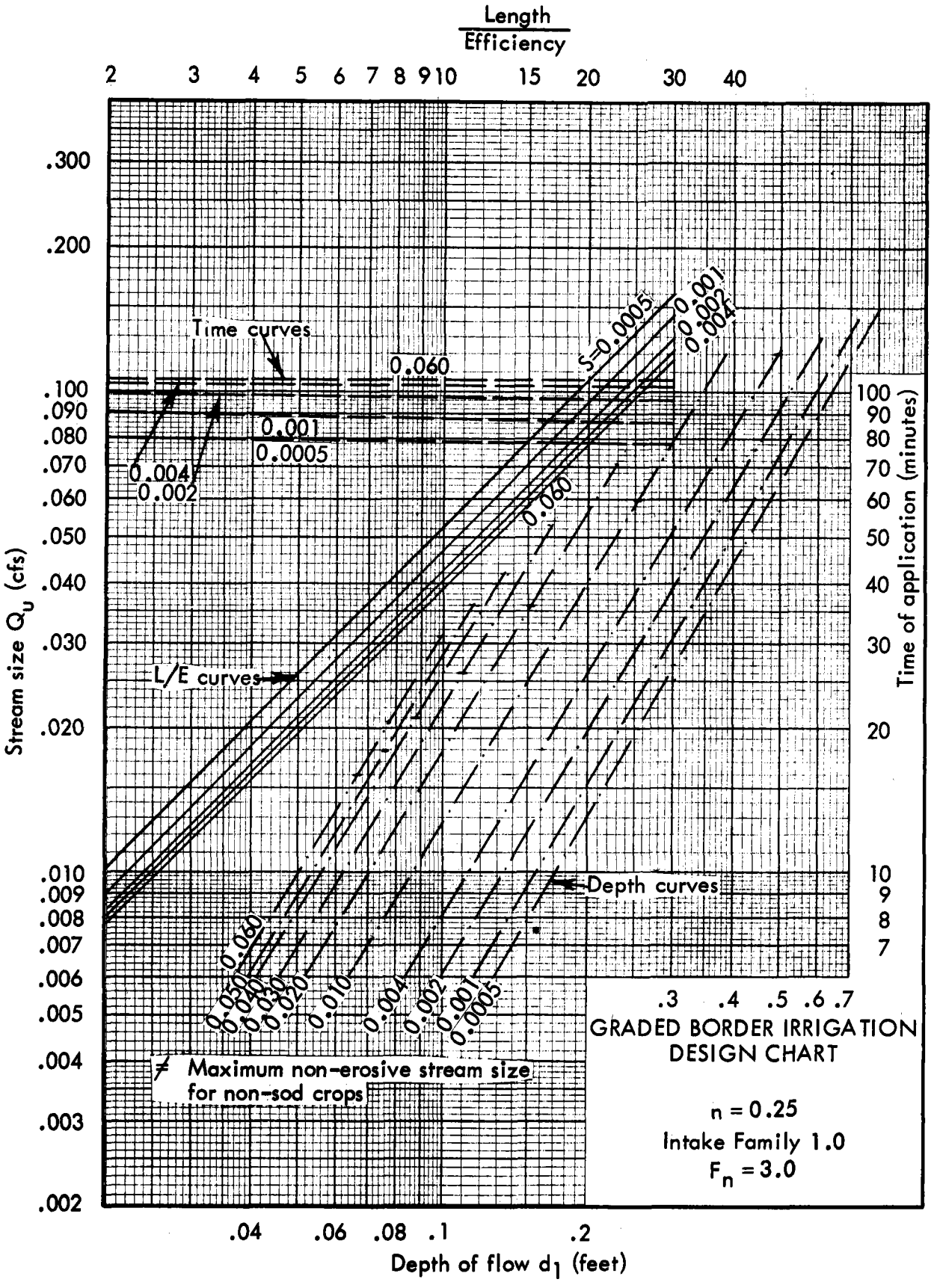

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.023
0.002
0.001
0.0005
Maximum non-erosive stream size for non-sod crops
S=0.0005
0.001
L/E curves
0.002
0.023
Depth curves
0.023
0.020
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
.04 .06 .08 .1 .2 .3 .4 .5 .6 .7
Depth of flow d_1 (feet)
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 3.0

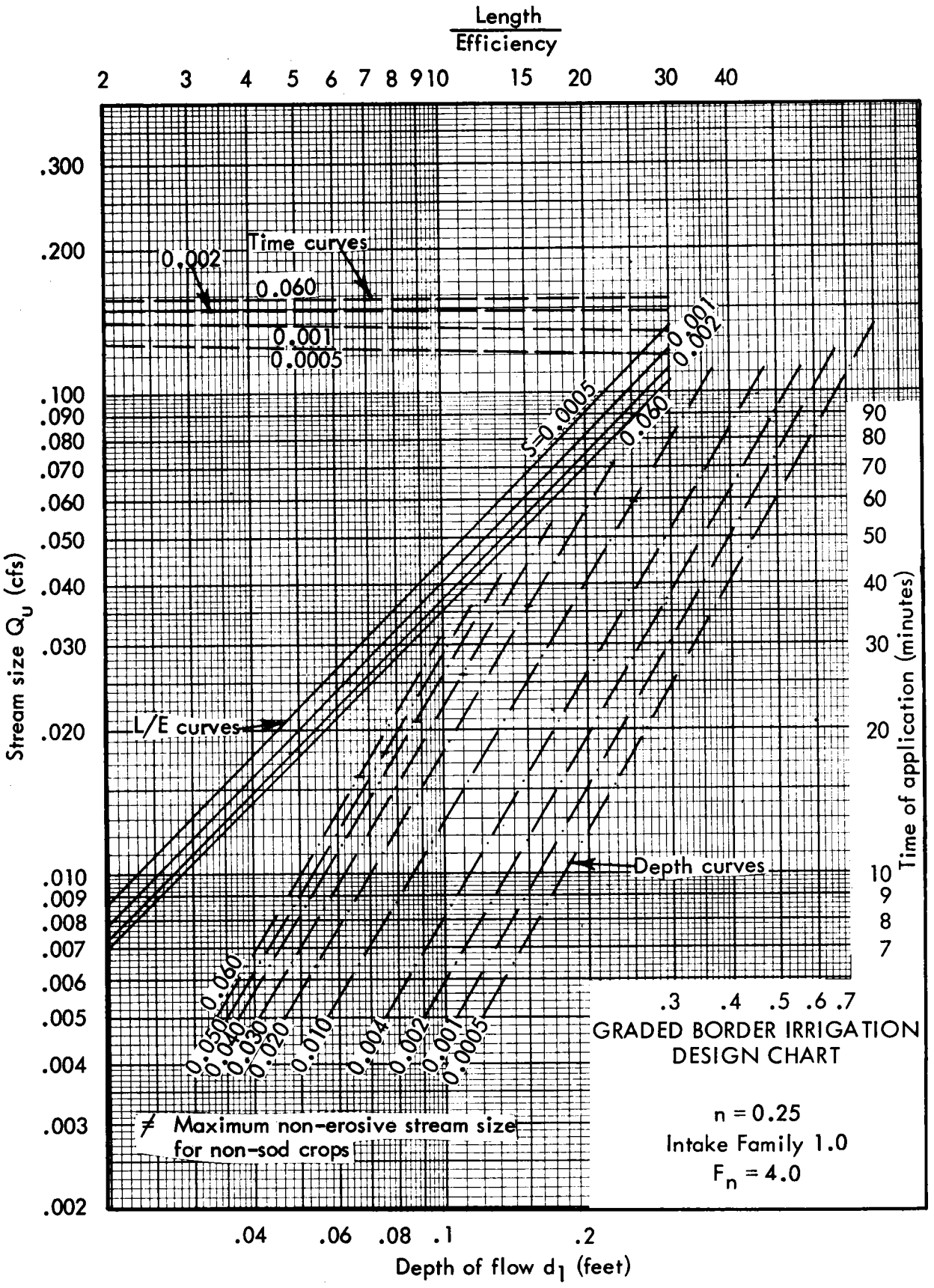

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.018
0.0005
0.002 0.001
L/E curves
Depth curves
S=0.0005
0.018
0.001
0.002
0.018
0.01
0.004
0.002
0.001
0.0005
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

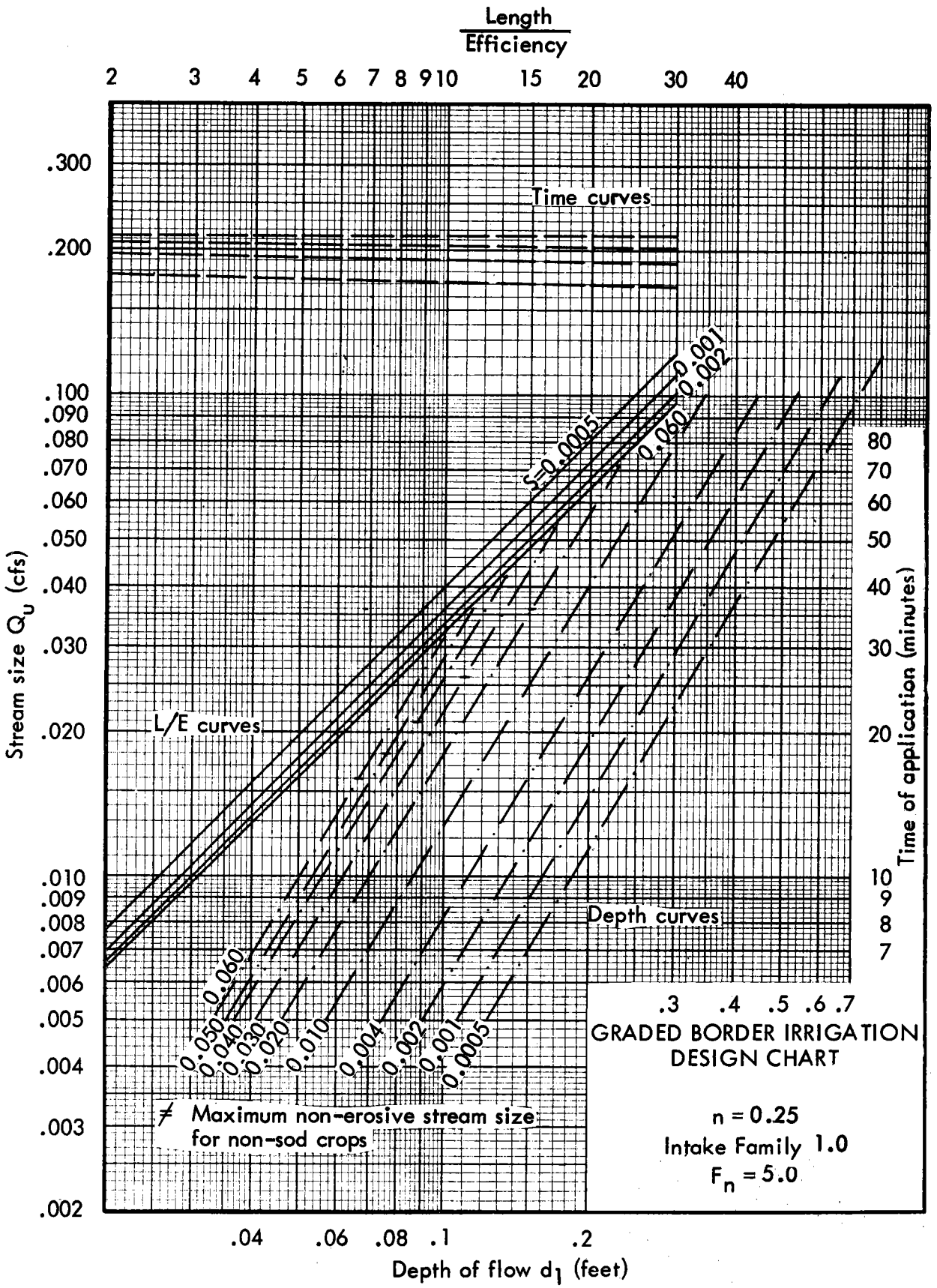

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
≠ Maximum non-erosive stream size for non-sod crops
Time curves
0.002
0.001
0.015
0.0005
L/E curves
0.0005
0.015
0.001
0.002
0.015
0.010
0.004
0.002
0.001
0.0005
Depth curves
2000
1000
900
800
700
600
500
400
300
200
100
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 0.5
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

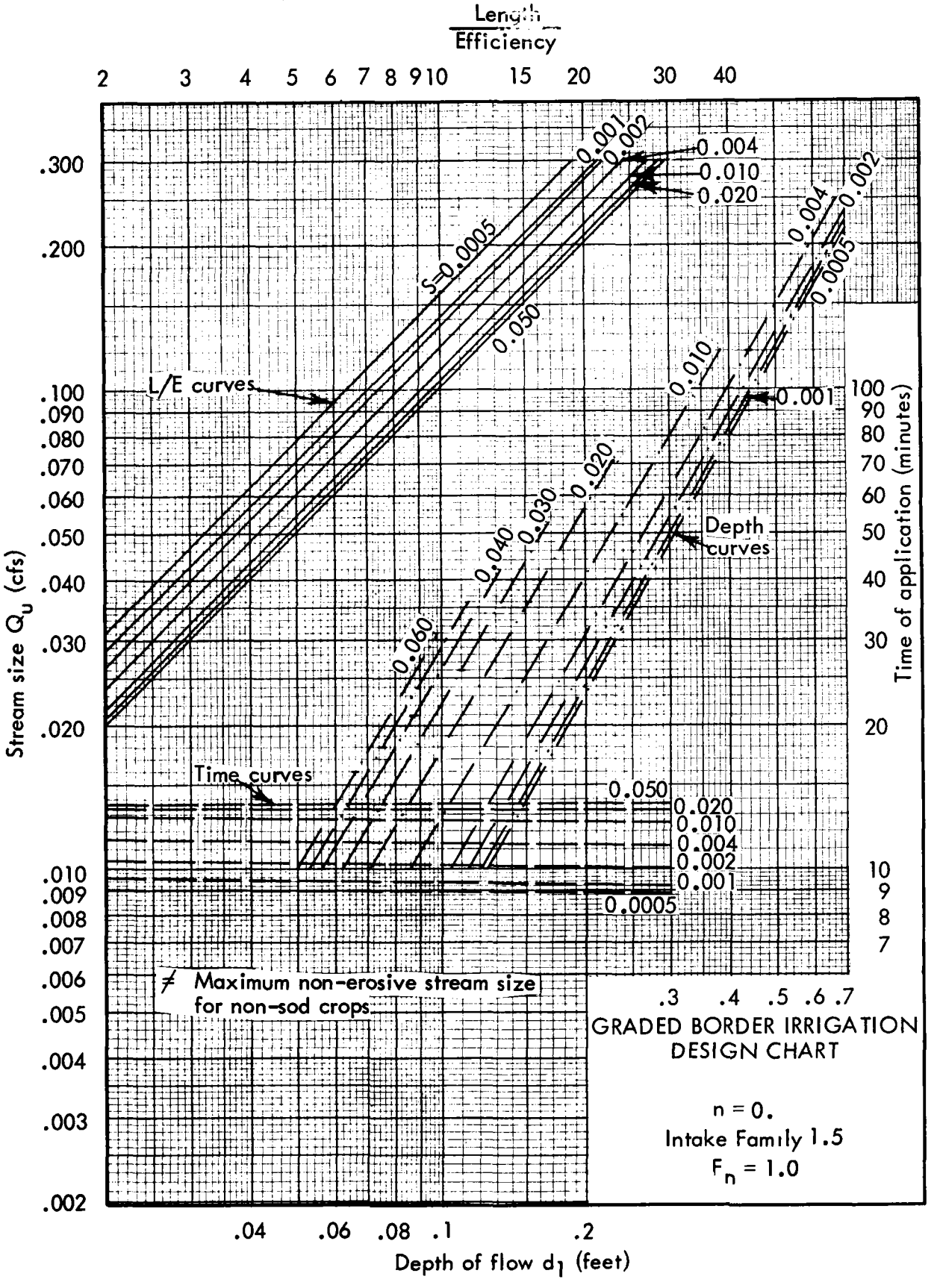

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
S=0.0005
0.001
0.002
0.004
0.010
0.060
0.020
0.030
0.040
0.050
L/E curves
Time curves
Depth curves
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
n =0.25
Intake Family 1.0
F_n = 1.0
≠ Maximum non-erosive stream size
for non-sod crops
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

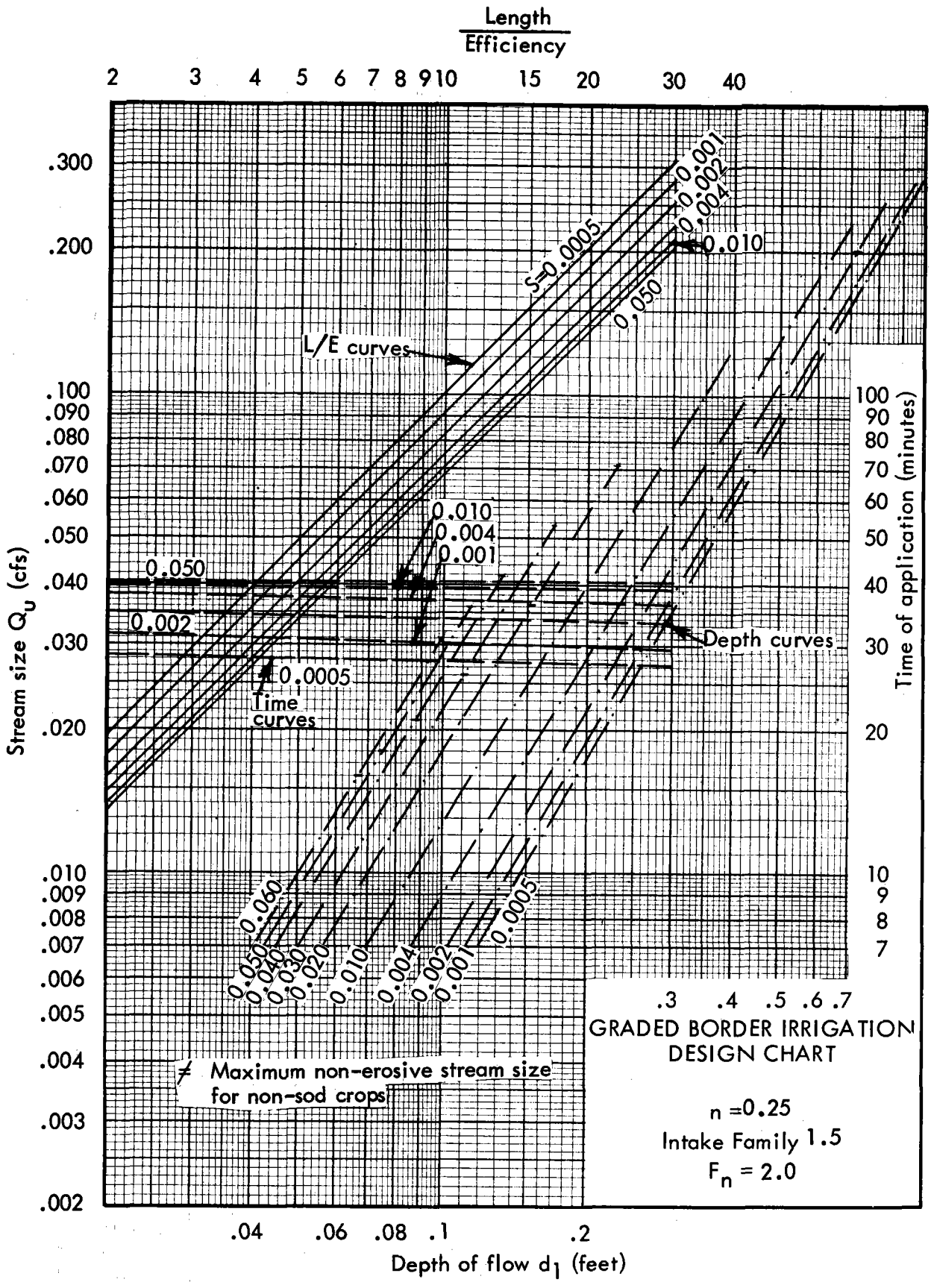

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
≠ Maximum non-erosive stream size for non-sod crops
S=0.0005
0.001
0.002
0.004
0.060
Time curves
0.004
0.002
0.060
0.001
0.0005
L/E curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
Stream size Q_u (cfs)
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Time of application (minutes)
100
90
80
70
60
50
40
30
20
10
9
8
7
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)

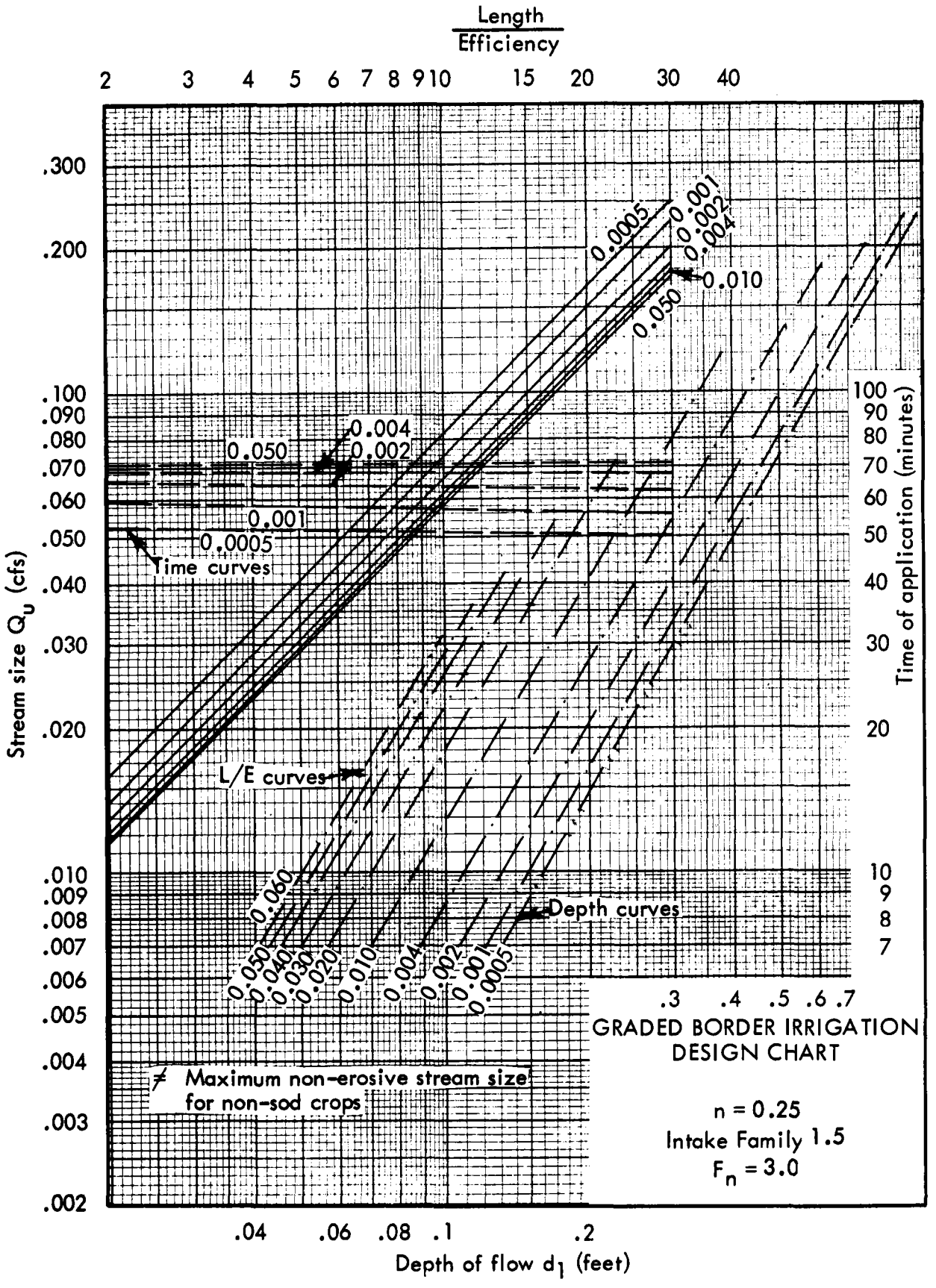

Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.060
0.001
0.0005
0.004
0.002
S=0.0005
0.001
0.002
0.004
0.060
L/E curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 3.0
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
100 90 80 70 60 50 40 30 20 10 9 8 7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
0.002
0.060
0.001
0.0005
S=0.0005
0.060
0.0001
0.0021
L/E curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 4.0
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
Time curves
S=0.0005
0.001
0.002
0.060
L/E curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.0
F_n = 5.0
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
80 70 60 50 40 30 20 10 9 8 7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
L/E curves
S=0.0005
0.001
0.002
0.004
0.010
0.020
0.050
Time curves
0.060
0.040
0.030
0.020
0.010
0.001
Depth curves
0.050
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.
Intake Family 1.5
F_n = 1.0


Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
.300
.200
.100
.090
.080
.070
.060
.050
.040
.030
.020
.010
.009
.008
.007
.006
.005
.004
.003
.002
Stream size Q_u (cfs)
S=0.0005
0.001
0.002
0.004
0.010
0.050
L/E curves
0.010
0.004
0.001
0.050
0.002
0.0005
Time curves
Depth curves
0.060
0.050
0.040
0.030
0.020
0.010
0.004
0.002
0.001
0.0005
≠ Maximum non-erosive stream size for non-sod crops
100
90
80
70
60
50
40
30
20
10
9
8
7
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
2 3 4 5 6 7 8 9 10 15 20 30 40
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Stream size Q_u (cfs)
100
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Time of application (minutes)
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Time curves
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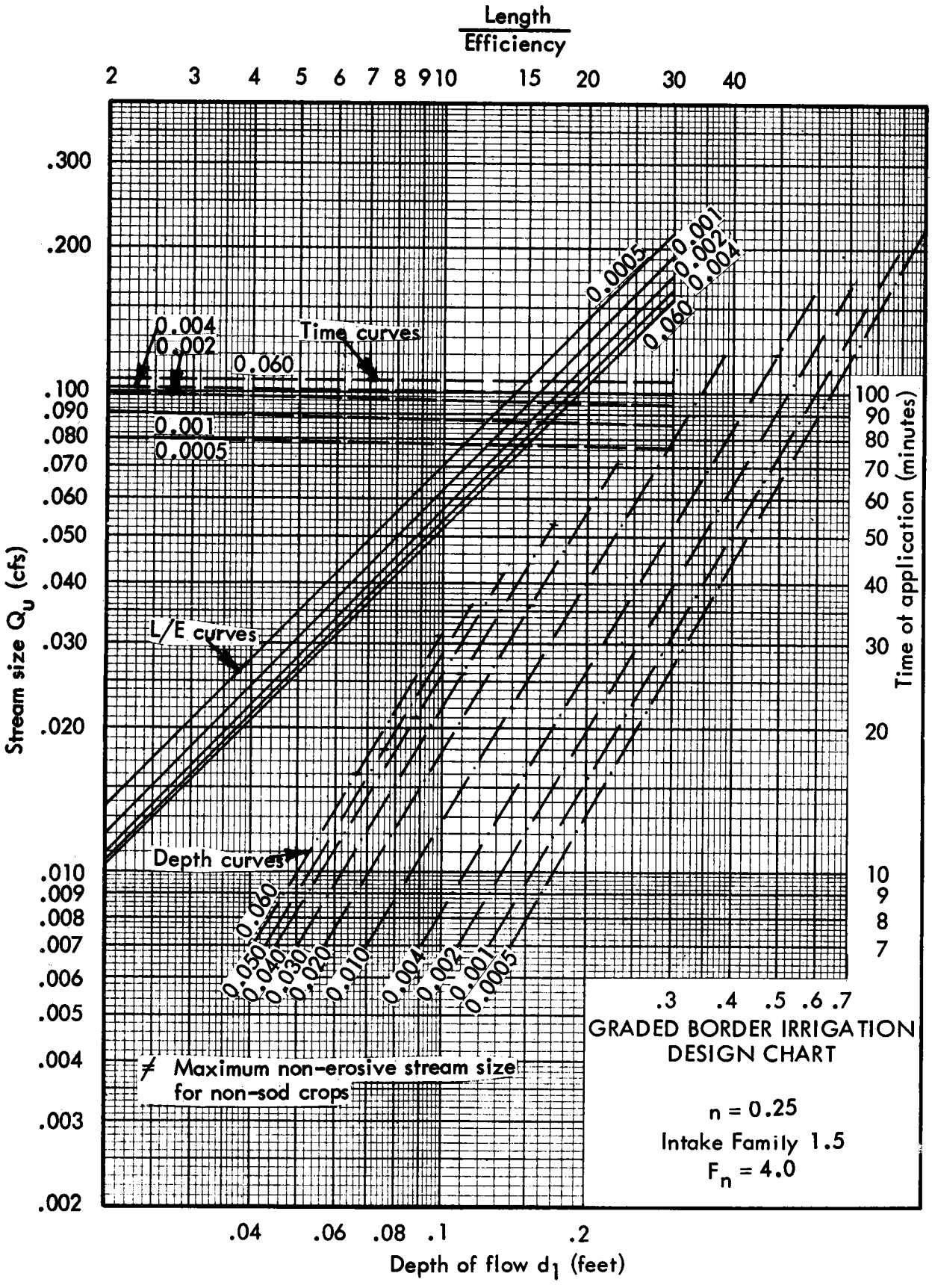
Depth curves
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION
DESIGN CHART
≠ Maximum non-erosive stream size
for non-sod crops
n = 0.25
Intake Family 1.5
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Stream size Q_u (cfs)
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Time curves
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≠ Maximum non-erosive stream size for non-sod crops
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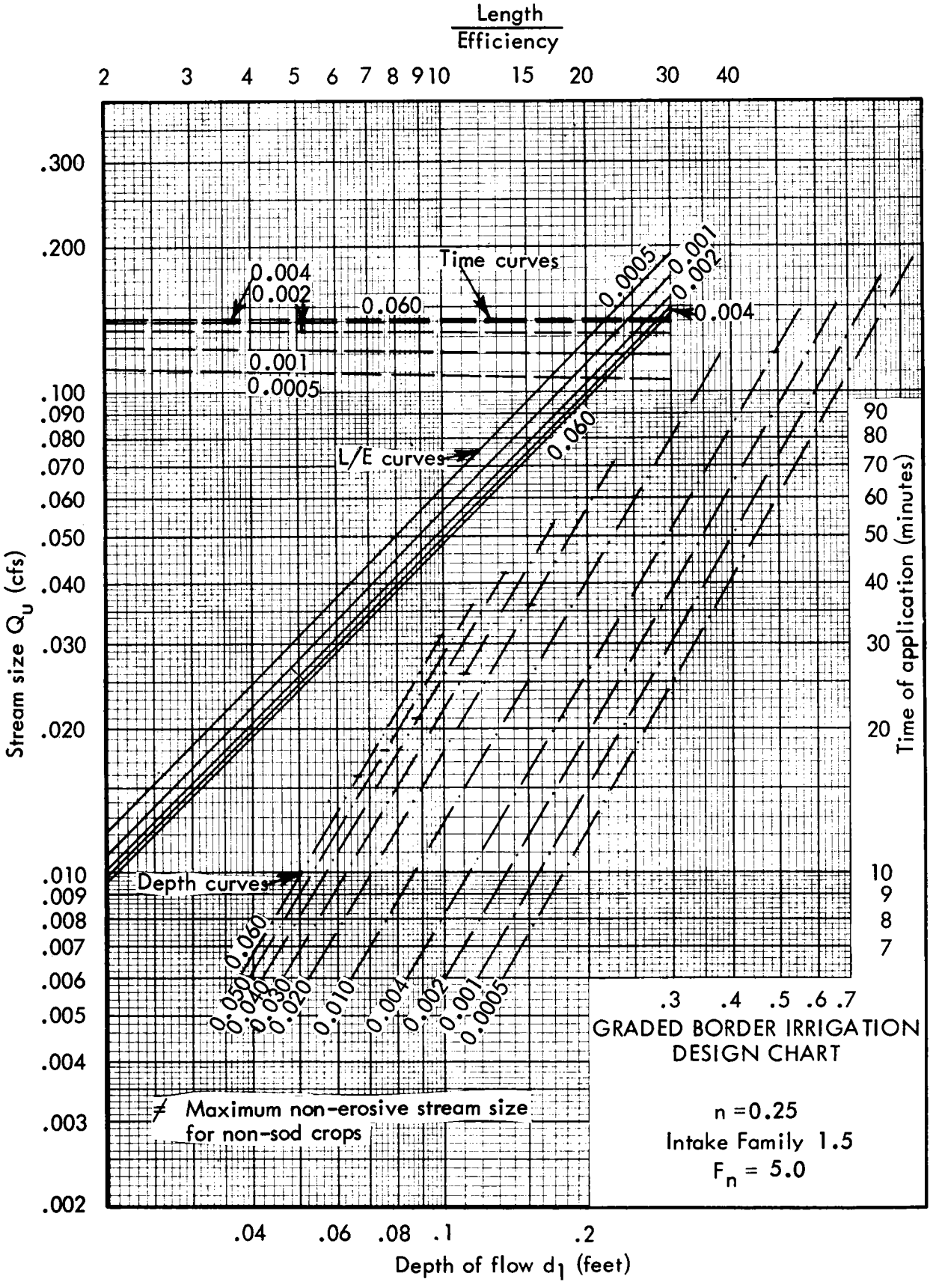
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Stream size Q_u (cfs)
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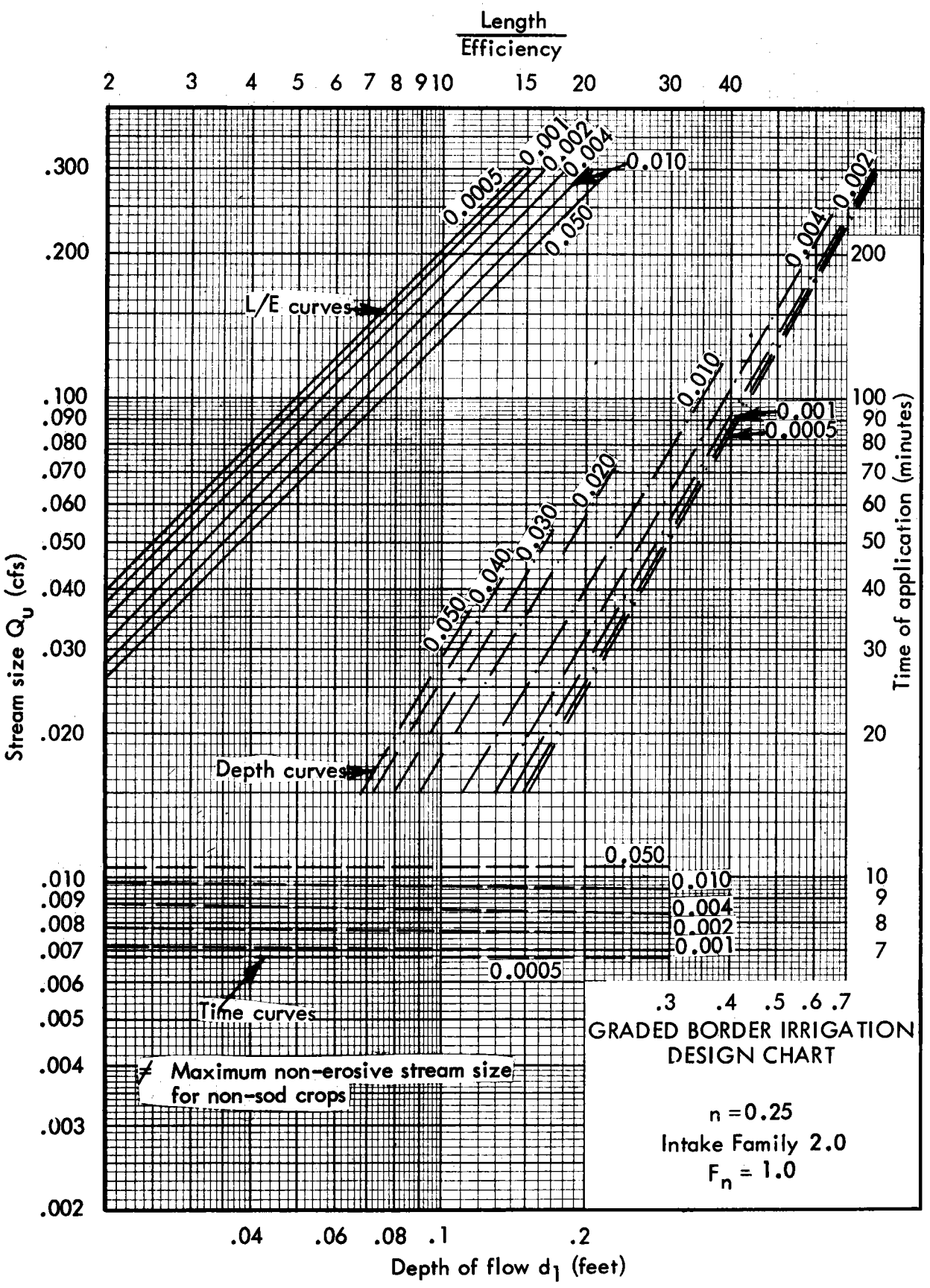
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 1.5
F_n = 5.0
≠ Maximum non-erosive stream size for non-sod crops
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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0.0005
Time curves
Maximum non-erosive stream size for non-sod crops
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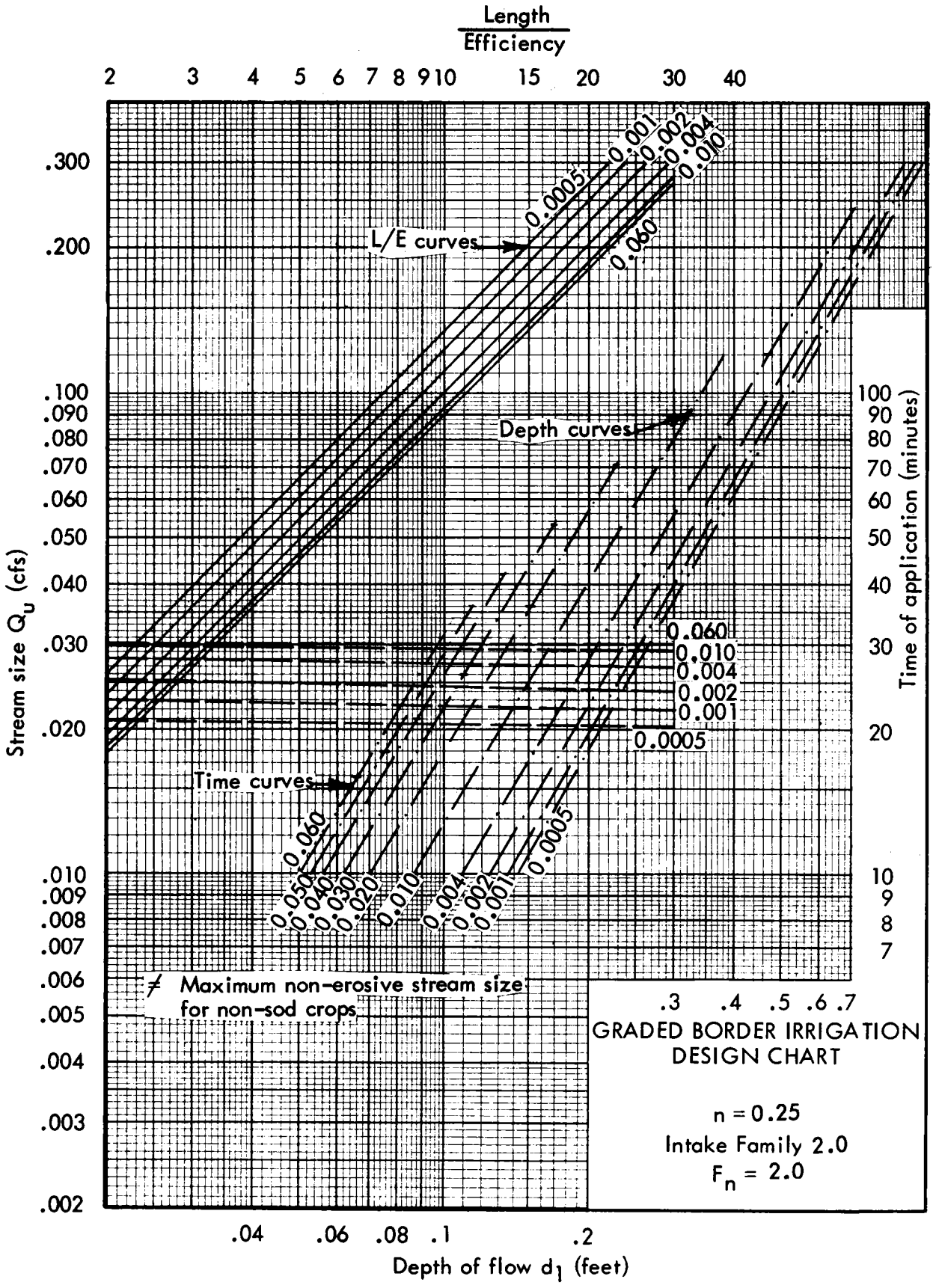
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 1.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Stream size Q_u (cfs)
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Depth curves
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Time curves
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≠ Maximum non-erosive stream size for non-sod crops
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Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
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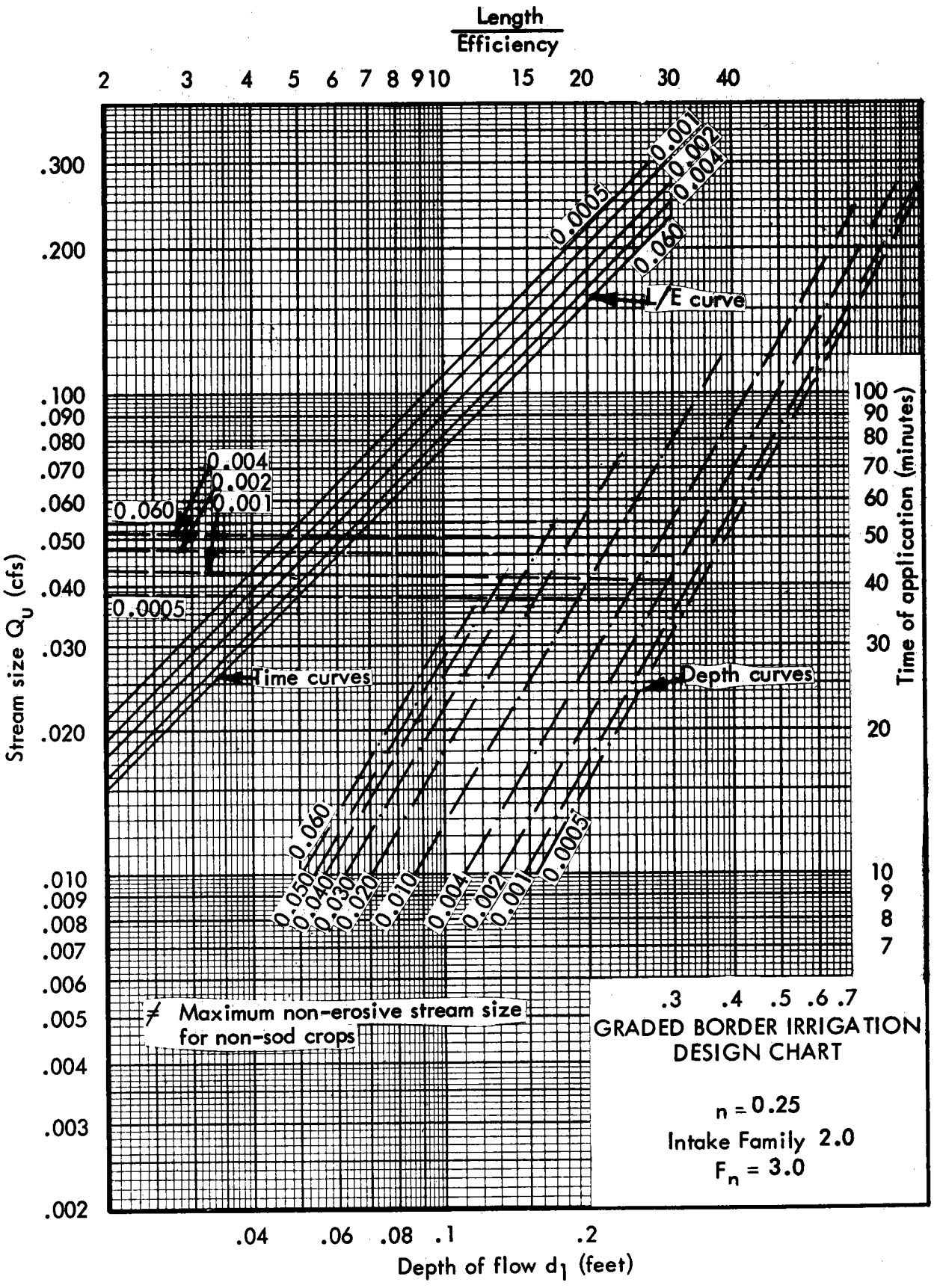
Intake Family 2.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
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Stream size Q_u (cfs)
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L/E curve
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0.0005
Time curves
Depth curves
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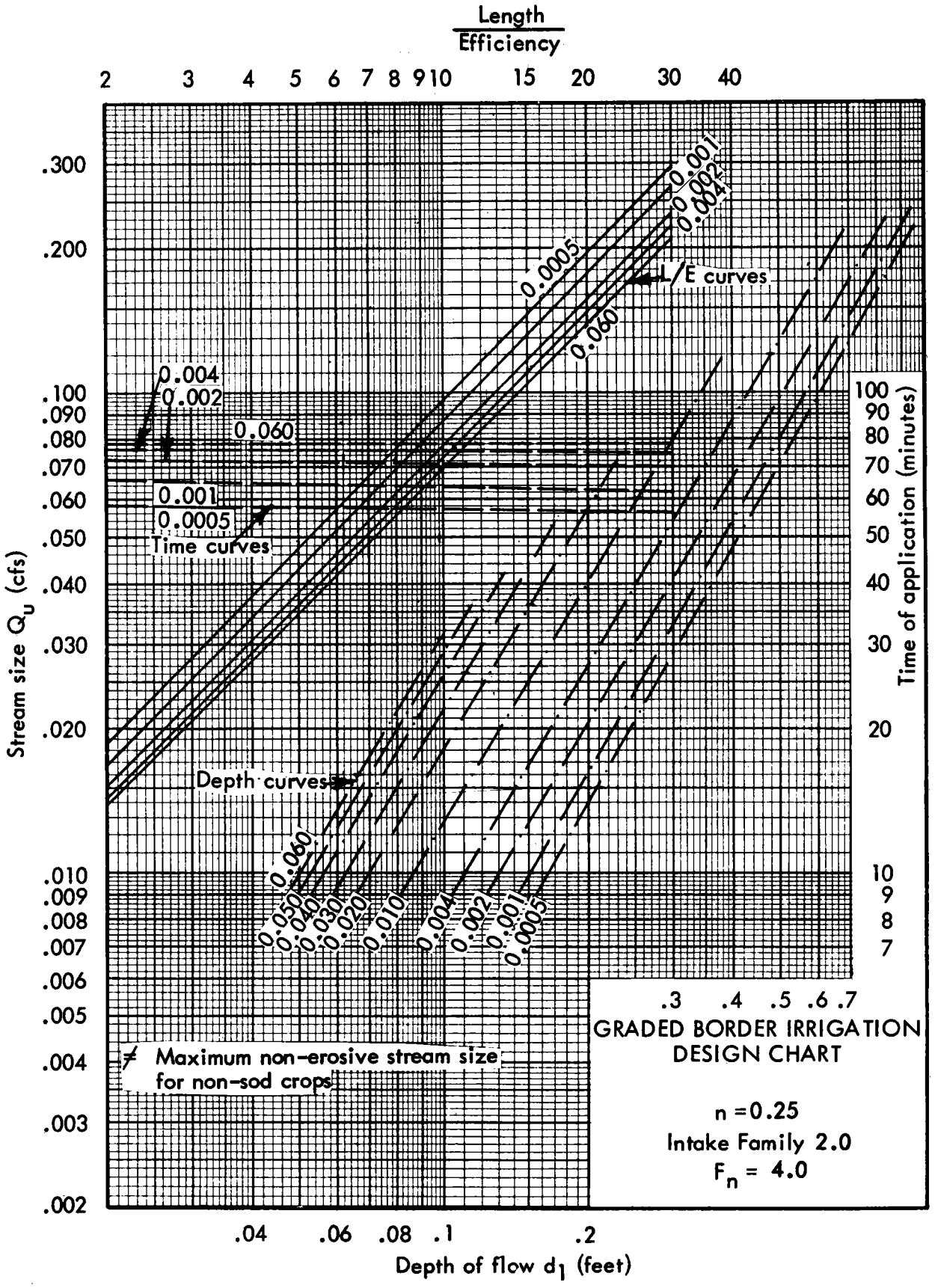
Time of application (minutes)
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 3.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
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Stream size Q_u (cfs)
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L/E curves
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Time curves
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Maximum non-erosive stream size for non-sod crops
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Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
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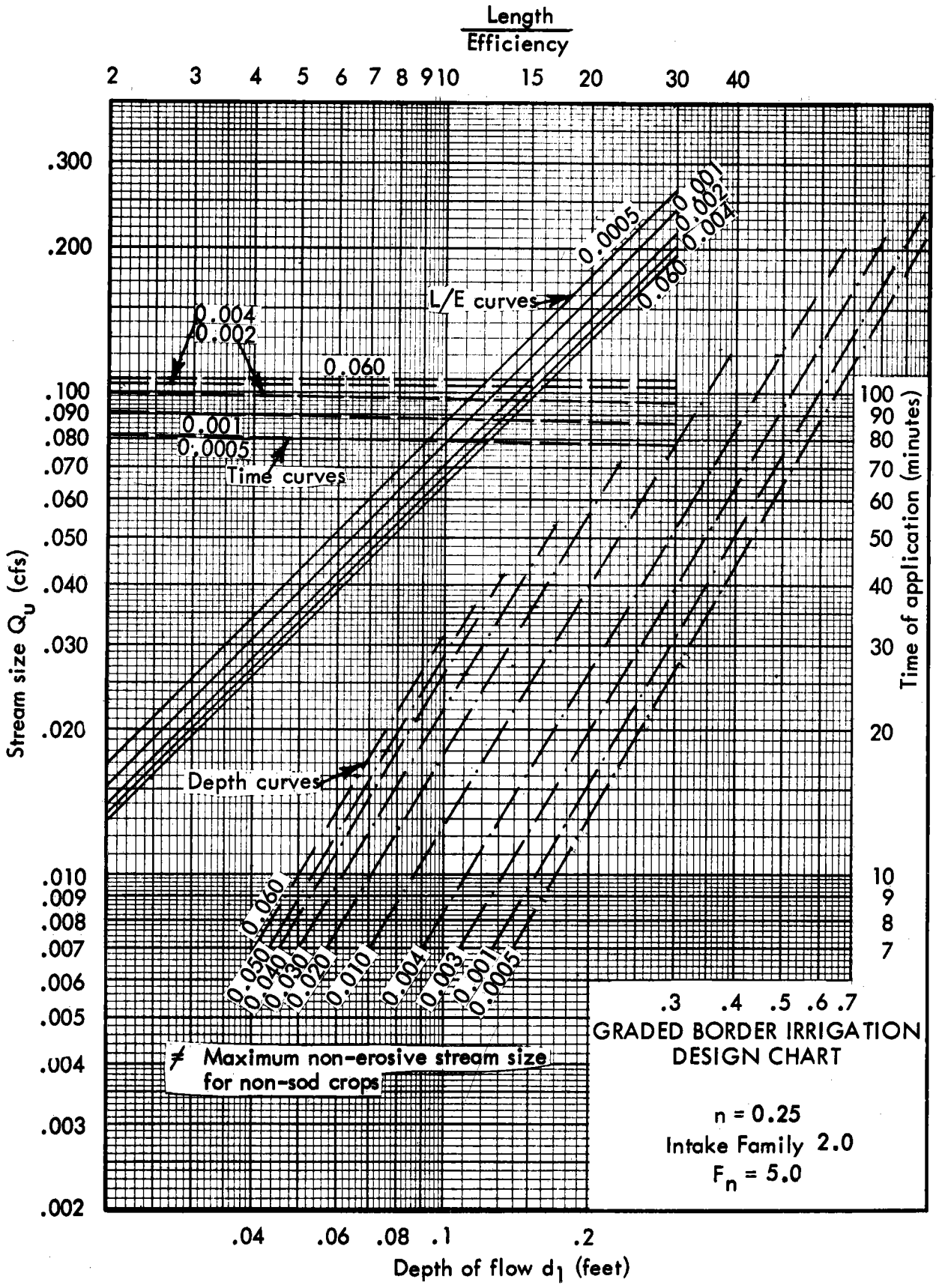
Intake Family 2.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)


Length / Efficiency
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Stream size Q_u (cfs)
Time of application (minutes)
100 90 80 70 60 50 40 30 20 10 9 8 7
L/E curves
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Time curves
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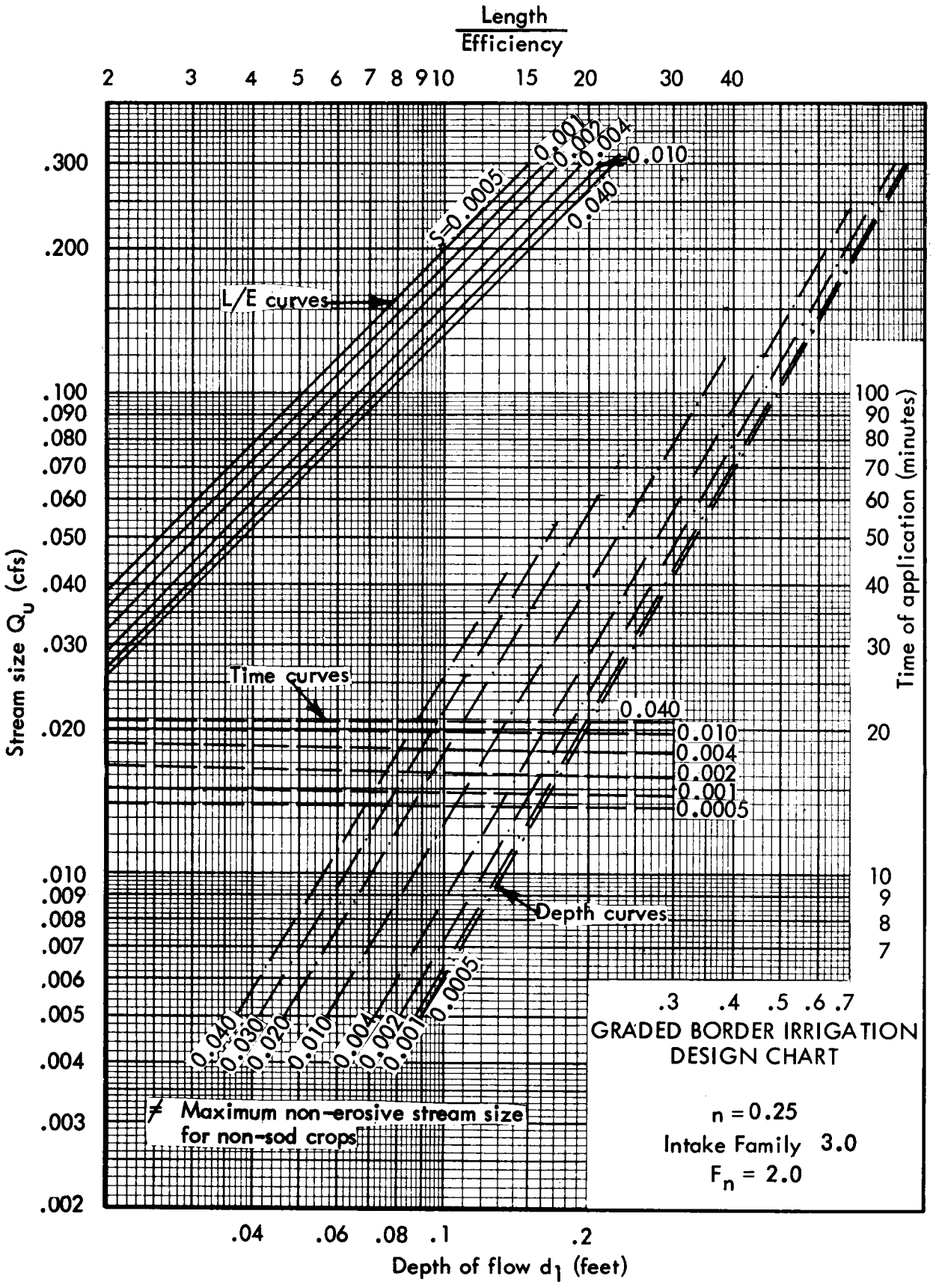
≠ Maximum non-erosive stream size for non-sod crops
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 2.0
F_n = 5.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Stream size Q_u (cfs)
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≠ Maximum non-erosive stream size for non-sod crops
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Time of application (minutes)
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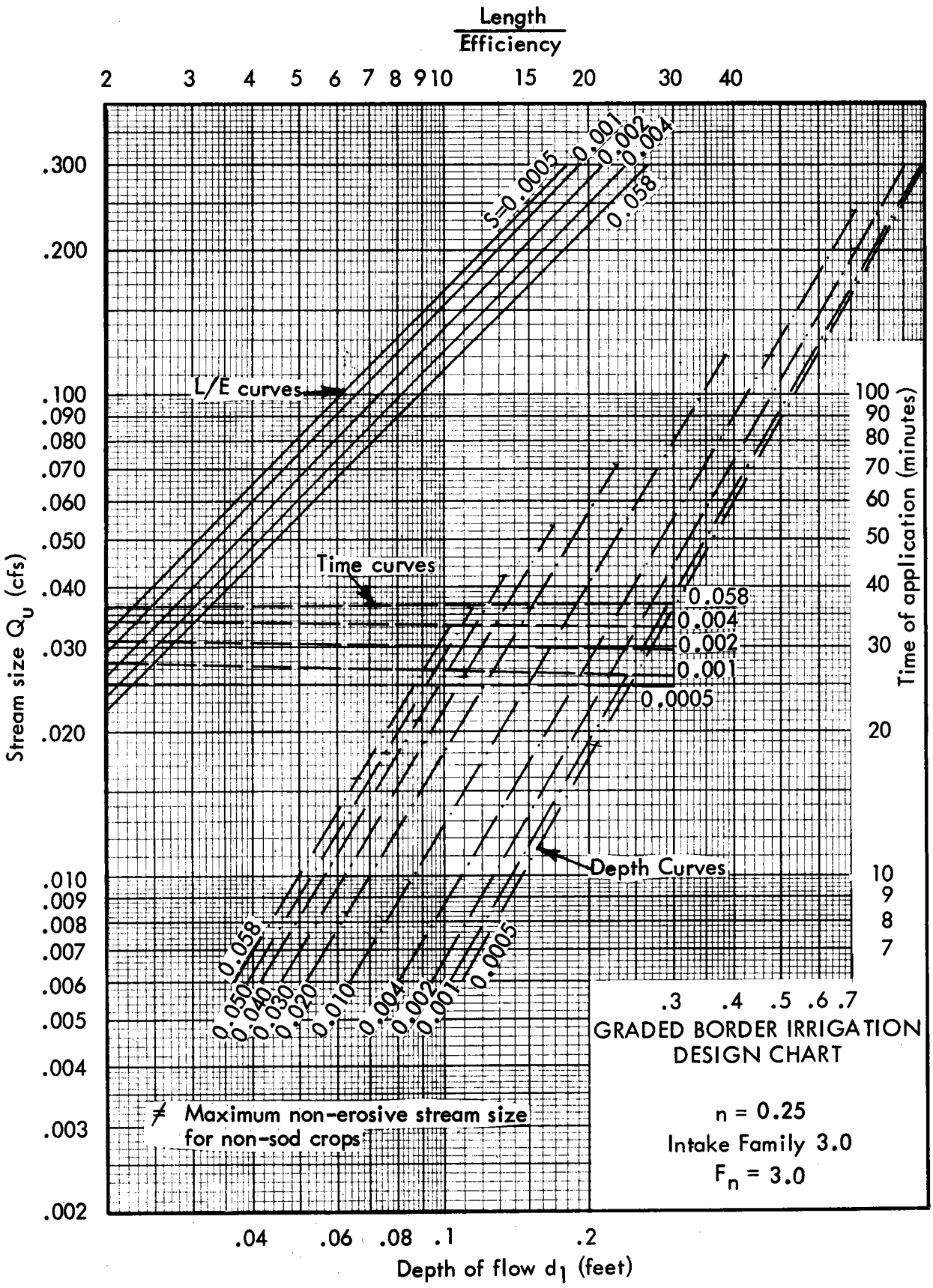
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 2.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Time of application (minutes)
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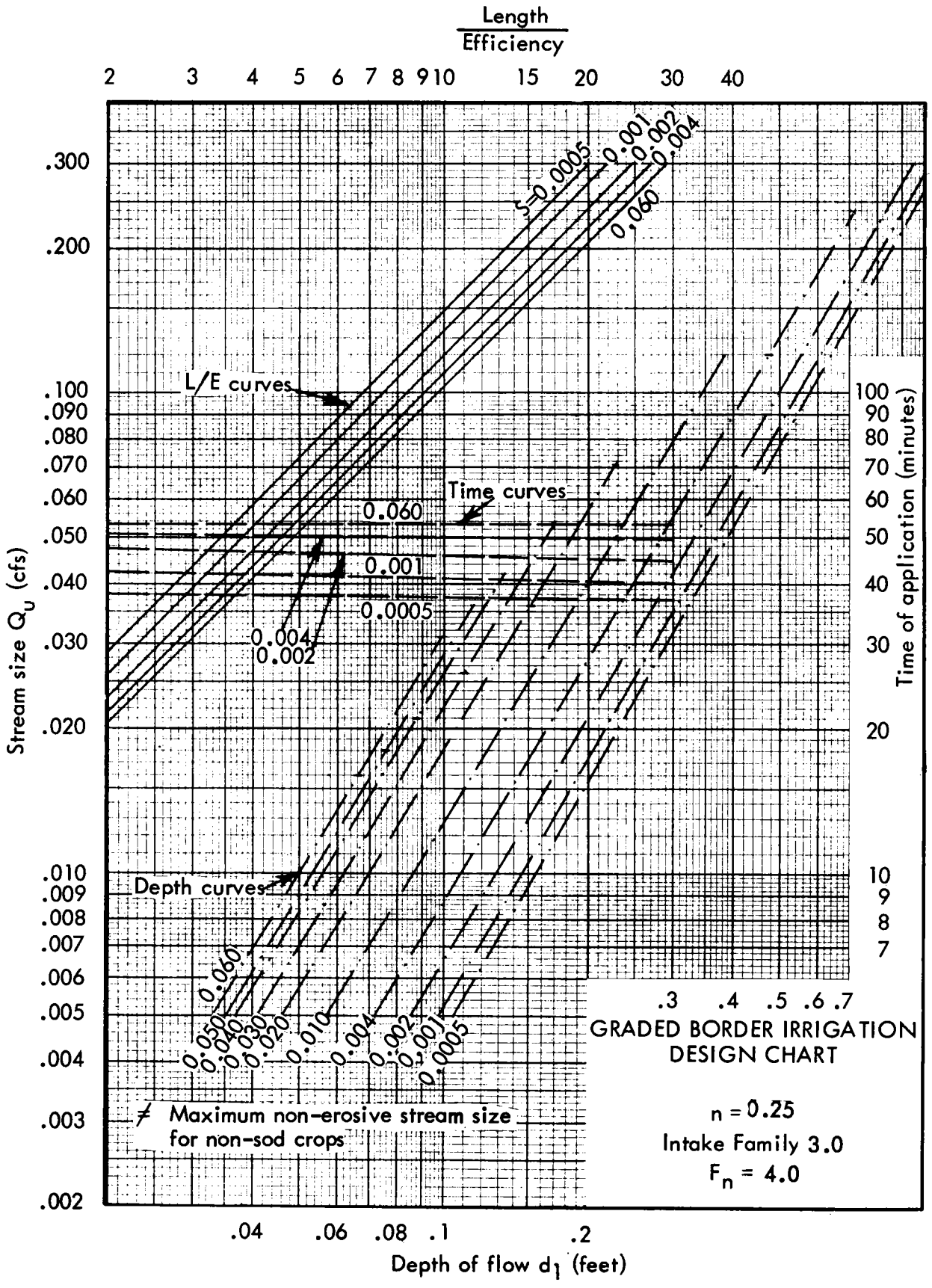
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 3.0
≠ Maximum non-erosive stream size for non-sod crops
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Stream size Q_u (cfs)
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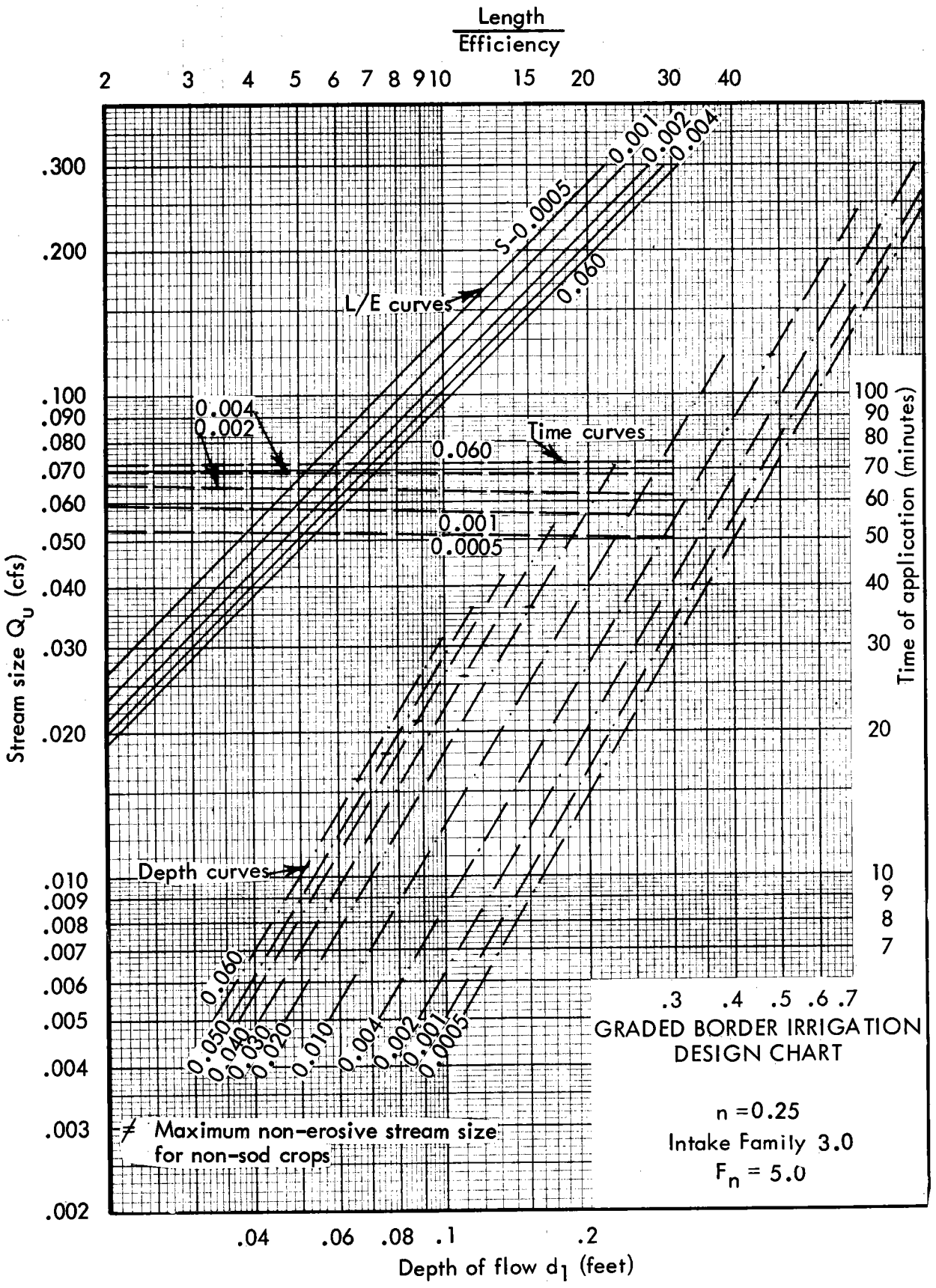
Time of application (minutes)
.3 .4 .5 .6 .7
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 3.0
F_n = 4.0
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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Time of application (minutes)
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GRADED BORDER IRRIGATION DESIGN CHART
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Intake Family 3.0
F_n = 5.0
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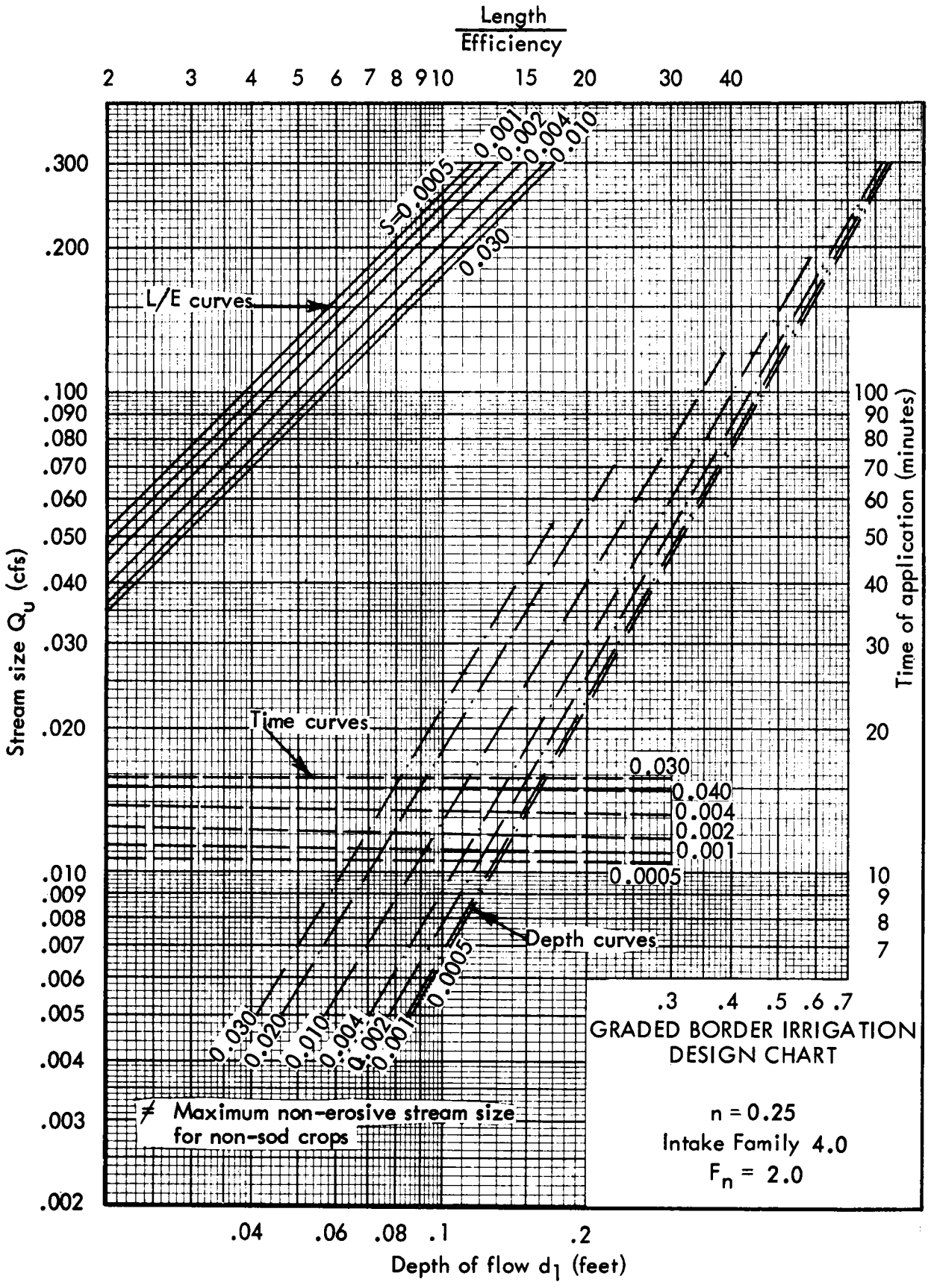
Depth of flow d_1 (feet)


Length / Efficiency
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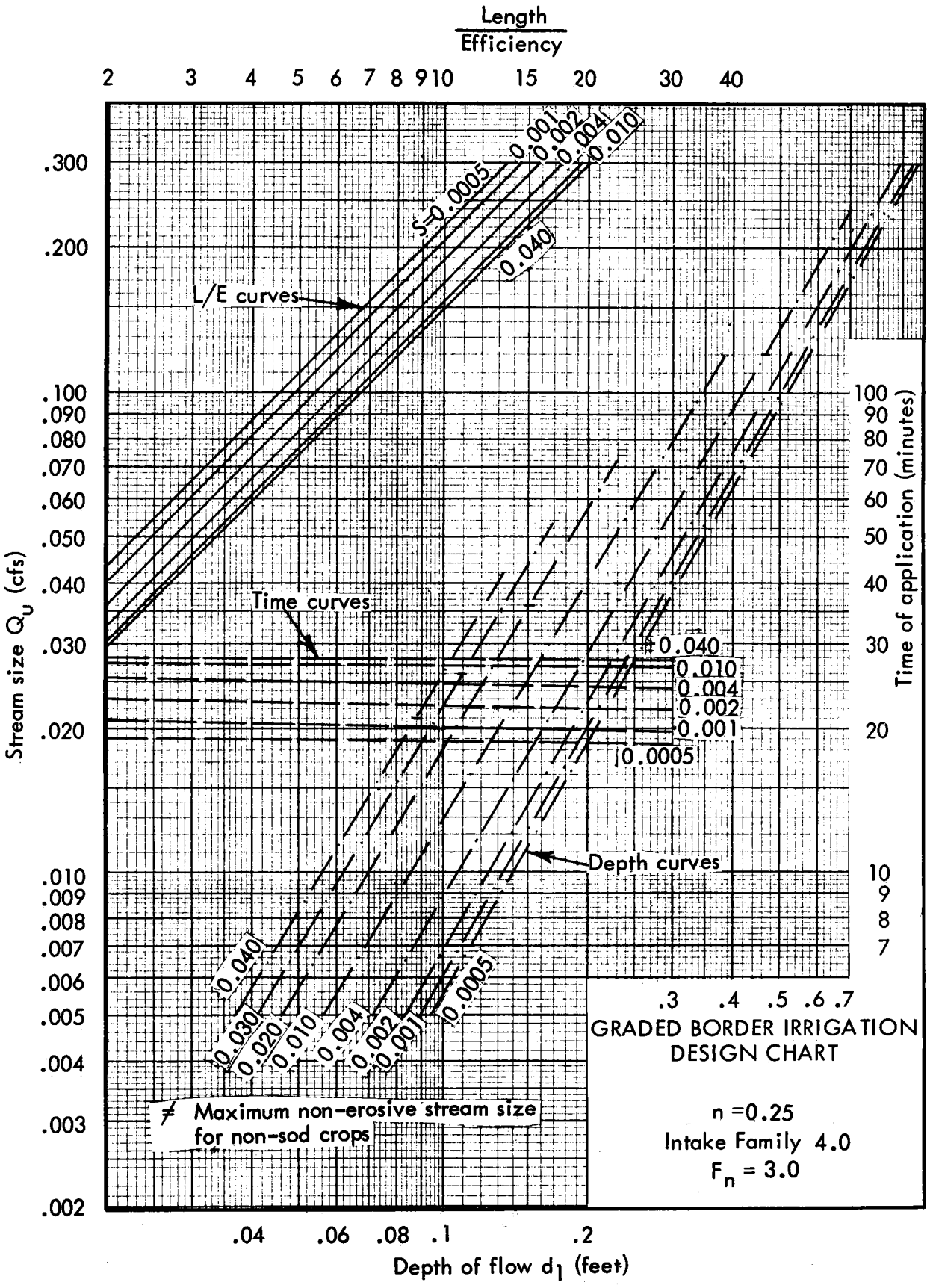
≠ Maximum non-erosive stream size for non-sod crops
GRADED BORDER IRRIGATION DESIGN CHART
n = 0.25
Intake Family 4.0
F_n = 2.0
Stream size Q_u (cfs)
.300 .200 .100 .090 .080 .070 .060 .050 .040 .030 .020 .010 .009 .008 .007 .006 .005 .004 .003 .002
Time of application (minutes)
100 90 80 70 60 50 40 30 20 10 9 8 7
.3 .4 .5 .6 .7
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)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F_n = 3.0
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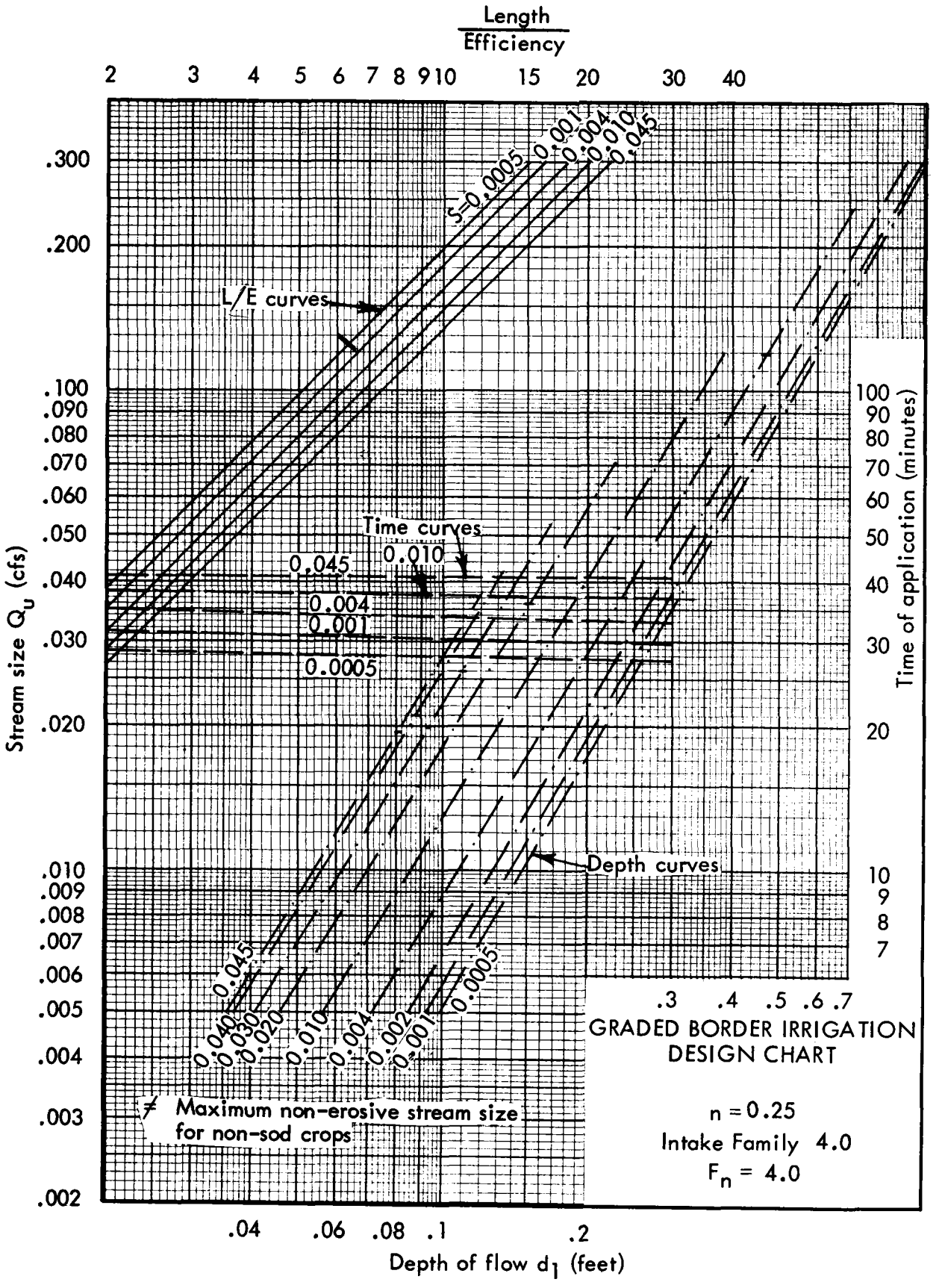
Depth of flow d_1 (feet)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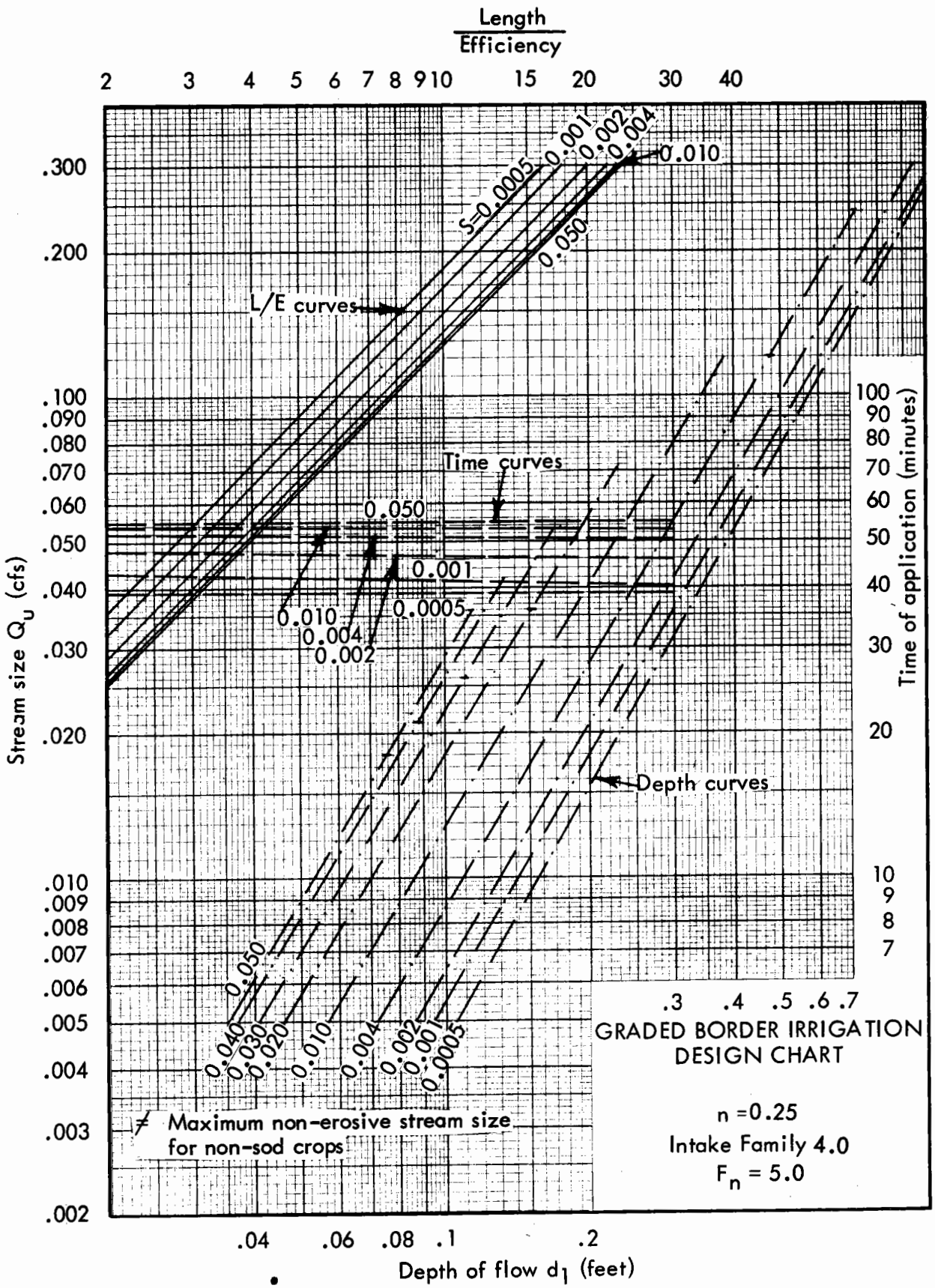
F_n = 4.0
≠ Maximum non-erosive stream size for non-sod crops
.04 .06 .08 .1 .2
Depth of flow d_1 (feet)



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Department of
Agriculture

**Soil
Conservation
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National
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Section 15

Irrigation

Chapter 5

Furrow Irrigation

Chapter 5
Furrow Irrigation

Contents

	Page
Figures	iv
Tables	iv
Nomenclature	v
Description	5-1
Adaptability	5-2
Climate	5-2
Soils	5-2
Topography	5-2
Crops	5-2
Water supply	5-3
Water quantity	5-3
Water quality	5-3
Advantages of furrow irrigation	5-4
Limitations of furrow irrigation	5-4
Kinds of furrow irrigation	5-5
Level furrows	5-5
Adaptability	5-5
Advantages	5-5
Limitations	5-5
Graded straight furrows	5-5
Adaptability	5-5
Advantages	5-6
Limitations	5-7
Graded contour furrows	5-7
Adaptability	5-8
Advantages	5-9
Limitations	5-9
Corrugations	5-10
Adaptability	5-11
Advantages	5-11
Limitations	5-12
Planning and design considerations	5-12
Land preparation	5-13
Layout and construction	5-13
Erosion control	5-13
Soil water intake characteristics	5-14
Physical features of soil	5-14
Cultural practices	5-14
Cropping practices	5-14
Soil water level	5-14
Water quality	5-15
Seasonal variation	5-15
Distribution of intake	5-15
Spacing	5-16
Furrow spacing	5-16
Corrugation spacing	5-17
Equivalent intake	5-17

Shape 5-17
Furrow shape 5-18
Corrugation shape 5-18
Grade 5-18
Furrow grade 5-18
Corrugation grade 5-19
Length 5-19
Furrow length 5-19
Corrugation length 5-22
Stream size 5-22
Furrow stream 5-22
Corrugation stream 5-23
Methods of water control 5-23
Cutback inflow 5-23
Impoundment 5-23
Continuous inflow and recovery 5-25
Application depth 5-25
Assumptions 5-25
Intake-time relationship 5-26
Advance time 5-26
Recession time 5-26
Opportunity time 5-27
Retardance coefficient 5-27
Wetted perimeter 5-27
Intake-family curves 5-27
Limitations 5-28
Deep percolation 5-28
Runoff 5-28
Design efficiency 5-28
Equations 5-28
Graded furrows 5-28
Summary of graded furrow equations 5-39
Design example of graded furrows 5-40
Procedure for using design charts 5-41
Cutback-inflow method 5-43
Summary of cutback-inflow equations 5-44
Design example of cutback inflow 5-45
Level impoundment furrows 5-46
Summary of level furrow equations 5-48
Design example of level furrows 5-48
Distribution system 5-53
Farm ditch 5-54
Pipelines 5-54
Related conveyance structures 5-54
Distribution structures 5-54
Application control structures 5-54

Automated farm systems 5-56
Drainage facilities 5-57
Outflow control 5-57
Rainfall runoff 5-57
Irrigation runoff 5-57
Subsurface drains 5-58
Tailwater recovery 5-58
Intake evaluation 5-60
Site selection 5-60
Soil conditions 5-60
Cropping history 5-60
Flow measurements 5-60
Flow control 5-60
Procedures 5-60
Computation and evaluation 5-61
Glossary 5-71
Appendix—computer programs 5-75
Graded furrow design 5-75
Level furrow design 5-80
Cutback furrow design 5-90

Figures

		Page
5-1	Climatic areas	5-3
5-2	Level furrow irrigation	5-6
5-3	Graded straight furrows	5-7
5-4	Graded straight furrows across the slope	5-8
5-5	Benches to support furrows on sloping fields	5-9
5-6	Graded contour furrows	5-10
5-7	Corrugation irrigation	5-11
5-8	Moisture penetration patterns	5-16
5-9	Variation in moisture penetration	5-16
5-10	Two-year, 30-minute rainfall	5-20
5-11	Two-year, 6-hour rainfall	5-21
5-12	Maximum furrow lengths	5-22
5-13	Furrow stream velocity and flow depth	5-24
5-14	Application time, advance and recession time vs. intake relationship	5-26
5-15	Intake-family curves	5-29
5-16	Advance time vs. length	5-32
5-17	Graded furrow design chart	5-42
5-18	Graded furrow design chart	5-42
5-19	Cutback-inflow furrow design chart	5-47
5-20	Level impoundment furrow design chart	5-53
5-21	Discharge of aluminum siphon tubes	5-55
5-22	Plan for a return flow system	5-59
5-23	Furrow-intake data sheet	5-62
5-24	Furrow-intake evaluation—flow data example 1	5-64
5-25	Furrow-intake evaluation—soil water	5-66
5-26	Cumulative intake vs. time, evaluation examples	5-67
5-27	Furrow intake evaluation—flow data example 2	5-68
5-28	Cumulative inflow, outflow, and intake—evaluation example 2	5-70

Tables

5-1	Maximum corrugation spacing (inches)	5-17
5-2	Conversion—cubic feet per foot of furrow to inches of equivalent depth	5-17
5-3	Required furrow cross-sectional area in square feet	5-18
5-4	Furrow storage in gallons per foot length	5-18
5-5	Runoff for inches of rainfall (Curve No. 75)	5-20
5-6	Runoff for inches of rainfall (Curve No. 80)	5-20
5-7	Runoff for inches of rainfall (Curve No. 85)	5-21
5-8	Wetted perimeter plus constant (feet)	5-30
5-9	Furrow-intake family and advance coefficients	5-31
5-10	Level furrows	5-49

Nomenclature

A = Area in square feet

a = Intercept of cumulative intake at unit time

AE = Application efficiency in percent

AE_c = Cutback application efficiency in percent

ASW = Available soil water

AWC = Available soil water capacity

B = Bottom width of furrow or corrugation in feet

b = Exponent of time in intake equation

c = Advance coefficient depending on furrow-intake family

D = Depth of flow in feet

d = Advance coefficient depending on furrow-intake family

Da = Average depth of flow in feet

DE = Design efficiency

DP = Deep percolation loss in inches

DP_c = Cutback deep percolation in inches

DU = Distribution uniformity

ET = Evapotranspiration

F = Cumulative intake in inches

F_g = Gross depth of irrigation in inches

F_{gc} = Cutback gross application in inches

F_n = Design application depth in inches

F_{nc} = Cutback design application in inches

$F_{(0-L)}$ = Average intake over a reach L feet long

$F_{(0-L)c}$ = Cutback average intake over a reach L feet long

$F_{(0-x)}$ = Average intake over a reach x feet long

F_x = Intake depth for any point x

IE = Irrigation efficiency

I_f = Furrow-intake family number

L = Furrow length in feet

ln = Logarithm (natural)

MAD = Management allowed deficiency

n = Roughness coefficient in Manning equation

P′ = Wetted perimeter in furrow in feet

P = Wetted perimeter plus constant in feet

P_1 = Wetted perimeter plus constant for $\frac{Q}{2}$ in feet

P_e = Effective precipitation in inches

Q = Irrigation stream or inflow rate for a furrow or corrugation in gallons per minute

RO = Surface runoff depth from the furrow or corrugation in inches

RO_c = Cutback runoff in inches

r = Hydraulic radius

S = Slope of furrow or corrugation in feet per foot

SWD = Soil water deficiency

T_i = Time of application or inflow time in minutes

T_{ic} = Cutback time of application or inflow time in minutes

T_n = Opportunity time in minutes required for cumulative intake of F_n inches

T_{nc} = Cutback opportunity time required for cumulative intake of F_n inches

T_o = Intake opportunity time in minutes

$T_{(0-L)}$ = Average opportunity time for the furrow length L in minutes

$T_{(0-x)}$ = Average intake time for length 0 to x in minutes

T_{ox} = Intake opportunity time at point x along furrow length in minutes

$T_{o_{adv}}$ = Average opportunity time during the advance period in minutes

$T_{o_{ave}}$ = Average intake opportunity time in minutes

T_r = Recession time in minutes

T_t = Time of advance or travel in minutes

T_{tc} = Cutback time of advance or travel in minutes

$T_{t_{ave}}$ = Average time of advance

V = Velocity of flow in feet per second

v = Volume of water in cubic feet

v_{RO} = Volume of surface runoff in acre-feet

v_s = Volume of surface storage in gallons

W = Furrow or corrugation spacing in feet

x = Furrow length to point x

z = Side horizontal distance divided by vertical distance

Chapter 5

Furrow Irrigation

Description

Furrow irrigation is a method of applying water at a specific rate of flow into shallow, evenly spaced channels. These small channels convey the water down or across the slope of the field to the vicinity of plants growing in the furrows or on the beds between the furrows. This method differs from border irrigation in that only part of the ground surface is covered with water. The water infiltrates the soil both vertically and horizontally. The furrow stream is applied until the desired application depth and lateral penetration are obtained. How long water must be applied in the furrows depends on the volume of water required to fill the soil to the desired depth, the intake rate of the soil, and the spacing of the furrows. Land grading to provide uniform slopes is essential to permit uniform water application and efficient irrigation.

Furrow irrigation consists of four kinds of systems that are used according to the crops and furrows needed to distribute the irrigation water. Level, graded straight, and graded contour furrows are used primarily to irrigate clean-tilled crops planted in rows with one furrow between crop rows. For bedded crops where two rows are planted on each bed, the furrows are along each pair of rows. The size and shape of the furrows vary with the crop grown, the equipment used, and the spacing between crop rows. Furrow irrigation also includes applying water to small grain or similar crops drilled on flat-top furrow beds where the water is applied either on the bare ground or on ground with low vegetative retardance conditions. Corrugation furrows are small, closely spaced irrigation channels used primarily to irrigate noncultivated, close-growing crops on moderately steep land. Corrugations are also commonly used to guide irrigation streams on bordered land where the design is based on the border method instead of the corrugation method. Corrugations are frequently formed after the crop has been seeded. For perennial crops they are reshaped as needed to maintain the desired channel cross section.

Water application principles are the same for all types of furrow irrigation; furrow spacing, size and shape, and retardance characteristics are the primary differences. Corrugation streams are smaller than furrow streams. Because of the smaller channel generally used and the resistance to flow caused by the growing crop, the length of run is relatively short.

Adaptability

The adaptability of furrow irrigation to a specific site depends on climate, soils, topography, crops to be grown, and water supply.

Climate

Aside from the fact that climatic factors generally are of prime importance in determining the need for irrigation, precipitation and wind may also affect suitability as well as the design criteria. If precipitation occurs at an intensity and volume that result in either surface runoff and excessive soil erosion where runoff is concentrated in the channels or in crop damage from flooding, these conditions must be considered in determining which furrow method is suitable for a given climatic area. The requirements for erosion control or protection against flooding may impose severe restrictions on the use of furrow irrigation. Corrugations are seldom used on slopes of less than 1 percent. In areas of high rainfall the hazard of water erosion is high if corrugations are used on steeper slopes. Therefore, they are not recommended in the humid climatic areas except to irrigate perennial crops. The climatic areas to which specific restrictions apply are shown on the following generalized climatic area map (fig. 5–1).

Soils

Furrow irrigation is suitable for most irrigable soils if the soil depth and the surface topography permit the needed land leveling at an economically feasible cost and without permanent reduction of soil productivity. This method is best suited to medium to moderately fine-textured soils of relatively high available-water-holding capacity and intake characteristics that provide both lateral and vertical water penetration. These soil characteristics permit uniform irrigation with a minimum of water loss to deep percolation or surface runoff from the end of the rows.

In coarse-textured sands and loamy sands, irrigation water moves mainly downward and very little laterally. Efficient furrow irrigation on these soils requires a short run, a short application time, relatively narrow row spacing, and a small depth of water application. These severe limitations result in high labor and operating costs; therefore, furrow irrigation is not generally recommended on these soils.

Fine-textured, very slowly permeable soils present a different problem. Water must be impounded or a very small stream applied for long periods to obtain the desired intake. Unless a small stream is used, excessive surface runoff will require extensive tailwater recovery or safe disposal facilities. Many of these soils crack before they reach the moisture level at which irrigation is needed. These cracks frequently make it difficult to confine the irrigation water within the furrow. The restrictive features of these soils should be carefully considered before recommending any type of furrow irrigation. Corrugation irrigation is generally unsuitable on these types of soils.

Furrow irrigation generally is not recommended on soils containing high concentrations of salts. In most irrigated soils, salts are supplied from the waters being used and/or from the parent materials in which the soils formed. The irrigation water absorbs the salts from the soil; through capillary movement and subsequent evaporation of the water, the salts are concentrated in the surface soil of the furrow ridge where crop roots are most likely to be.

Topography

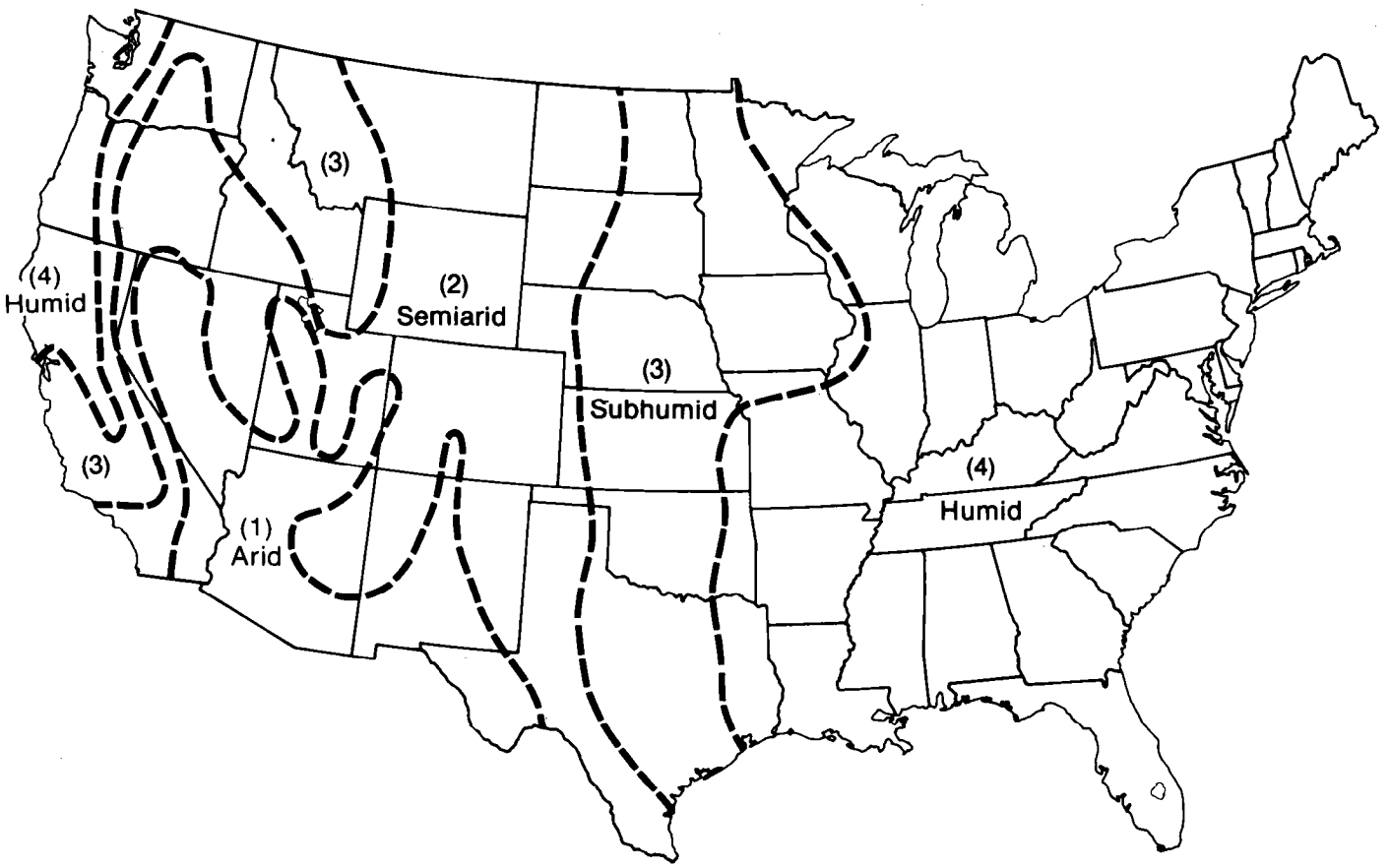
The topography of an individual field is an important consideration in determining the suitability of furrow irrigation. The topography must be such that within the grade limitations for the climatic area the rows can be laid out on a continuous grade. If land leveling is required to provide the design grade, the topography must be such that leveling does not expose unproductive soil or that the cost of leveling is not excessive. The topography must not be so steep that it exceeds the allowable corrugation grade or prohibits installation of graded contour furrows that meet the design grade and cross-slope criteria.

Crops

Furrow irrigation can be adapted for nearly all irrigated crops except those grown in ponded water, such as rice. Tillage, harvest, or other cultural

Figure 5-1

Climatic Areas



practices associated with the site may be so restrictive, however, that some other method of irrigation should be selected. Furrows are particularly suitable for irrigating crops subject to injury if water covers the crown or stems of the plants.

Water Supply

The quantity and quality of the water supply determine its suitability for use in furrow irrigation.

Water Quantity

Furrow irrigation can be used with any amount of water (either rate-of-flow or volume) if the acreage to be irrigated does not exceed the acreage for which the supply available can meet the needs of the crop to be grown.

If the systems are properly designed and water management is good, furrow irrigation can be as efficient as any other method of water application except a properly designed and managed trickle system. For maximum use of a limited water supply, alternate-row irrigation or other procedures can be used. Furrows are well suited to nearly any irrigation delivery rate because the number of rows irrigated in a set can be varied as needed.

Water Quality

Irrigation water may be of good quality or it may contain considerable amounts of colloidal material or various salts and minerals. Furrow irrigation can be

used if the water quality is good and, on some soils, if the water contains moderate amounts of colloidal materials. These colloidal materials will be deposited in the furrows and may materially decrease the intake rate of the soil. This can be to the irrigator's advantage when irrigating high-intake-rate soils such as sands. The colloidal materials may increase soil fertility and may make these soils easier to irrigate by allowing a longer furrow and increased application time. On other soils these materials may accumulate on the surface, making tillage more difficult and required more frequently.

Most irrigation water contains appreciable amounts of various salts or minerals that can be beneficial or harmful, depending on the kinds being carried. Plant use of soil moisture contributes to the accumulation of salts. Because most plants can select nitrate, potassium, and phosphate ions from the soil solution, these ions are seldom found in appreciable amounts in saline accumulations. Sodium, sulfate, and chloride ions, however, are taken up by the plants in very limited amounts. Evaporation from the soil surface and selective use by the plants cause these salts to accumulate in the furrow ridge. Most of the crop roots develop in the ridge where salts accumulate; therefore, furrow irrigation is not suitable if the water supply contains considerable amounts of detrimental salts such as sodium.

Advantages of Furrow Irrigation

Furrow irrigation has many advantages on suitable sites. Some of these are:

1. Irrigation streams can be large or small because the number of rows irrigated at one time can be adjusted as needed according to the available flow.
2. Efficient application can be obtained if water management practices are followed and the land has been properly prepared.
3. The initial capital investment is relatively low on lands not requiring extensive land leveling, since the furrows and corrugations are constructed by commonly used farm implements.
4. The water distribution systems do not normally require high water pressure to operate; therefore, pumping costs are relatively low.
5. Soils that form surface crusts when irrigated by flood methods can be readily irrigated by furrows because water moves across the row under the surface.
6. Water is not applied directly on the plants, thus eliminating scalding of the foliage and loss of insecticides.
7. Excellent field surface drainage is obtained where adequate outlet facilites are provided.
8. Alternate-row furrow irrigation allows the use of a greater part of the rainfall.

Limitations of Furrow Irrigation

Furrow irrigation also has certain limitations. Some of these are:

1. Salts from either the soil or water supply may concentrate in the ridges and depress crop yields.
2. The lateral spread of water in some soils is not adequate to provide full irrigation.
3. The difference in intake opportunity time along the furrow due to the time required for the stream to advance makes it difficult to obtain uniform application depths.
4. Corrugations create a rough field surface difficult to cross with harvesting and other farm equipment.
5. The soil-erosion hazard limits use to land having very little slope.
6. Labor requirements may be high because irrigation streams must be carefully regulated to achieve uniform water distribution.
7. Leaching of salts is difficult or impossible.
8. Land leveling is normally required to provide uniform furrow grades.

Kinds of Furrow Irrigation

There are four kinds of furrow systems: level furrows, graded straight furrows, graded contour furrows, and corrugations. Each system requires specific designs and layouts. The suitability of each depends on the topography, kind of soil, kind of crop, cultural practices, and climatic factors.

Level Furrows

Level furrows are small irrigation channels, with blocked or diked ends laid out with little or no grade (fig. 5–2). They generally require extensive land preparation and careful water management for successful operation. Irrigation water must be applied rapidly, using a stream as large as the furrow can contain, until the designed volume is applied. The ponded water stands at a uniform depth in the furrow until it is absorbed by the soil. Lateral or capillary movement of water throughout the soil distributes the water to areas between the furrows.

Adaptability

The level furrow is best suited to soils with a moderate to slow intake rate and moderate to high available-water-holding capacity. The topography must be relatively flat with smooth, uniform slopes. The crops most easily irrigated by level furrows are those grown in rows on beds between the furrows, because relatively large channels must be maintained to provide the necessary capacity. Level furrows are suited to all climatic areas except the humid area where a minimum grade is required to achieve the surface drainage needed to prevent crop damage or waterlogging of soils.

Advantages

The amount of water applied can be adjusted to the needed seasonal variations by changing the duration of application or the size of furrow stream, or both. No change in layout is needed. Efficient application can be obtained if the system is properly operated. No irrigation water need be lost through runoff. Maximum use can be made of rainfall even when the intensity of storms exceeds the soil intake rate. Provisions for disposal or reuse of tailwater are not needed. Water can be introduced at both ends of the furrows so that the furrow length can be twice the design length, which allows more efficient use of farm equipment. This method is well suited to automation.

Limitations

In areas where wind velocity exceeds 15 to 20 miles per hour, it is difficult to apply irrigation water if the wind blows in the opposite direction of water flow in the furrow. Some crops such as potatoes can be damaged by water ponded over the root system. Drainage of excess rainfall may require extensive water-disposal facilities. Furrow capacity must be large enough to carry rainfall excess without overtopping. Furrows should have adequate capacity for approximately one-half the volume of the net irrigation application. The irrigation application time must be short; therefore, frequent change of sets is required. The surface topography, furrow shape, and cross section must be carefully maintained. The farm operator must know about these specific needs and requirements for successful operation of the system.

Graded Straight Furrows

Graded straight furrows are small irrigation channels on relatively flat land laid out either in the direction of or across the slope of the land. They are constructed in a straight line, preferably parallel to a field boundary, and have a continuous, nearly uniform slope in the direction of irrigation. The length of time that water must flow in the furrows depends on the amount of water required to refill the root zone, the intake rate of the soil, and the rate of lateral spread of water in the soil. For most soils, the initial irrigating stream must greatly exceed the intake rate to provide an adequate advance rate that will result in a reasonably uniform intake-opportunity time along the furrow. When water reaches the lower end of the furrow, the flow rate must be reduced to prevent excessive runoff or provisions must be made to dispose of the tailwater safely or to recover and reapply it. Even where the streams are cut back, an appreciable amount of tailwater will collect. Therefore, a tailwater recovery system and provisions for safe disposal according to state regulations are normally integral parts of a graded furrow system.

Adaptability

Graded straight furrows can be used to irrigate all cultivated crops planted in rows. Graded furrows can be used on all soils except sands that have a very high intake rate and provide poor lateral spread of

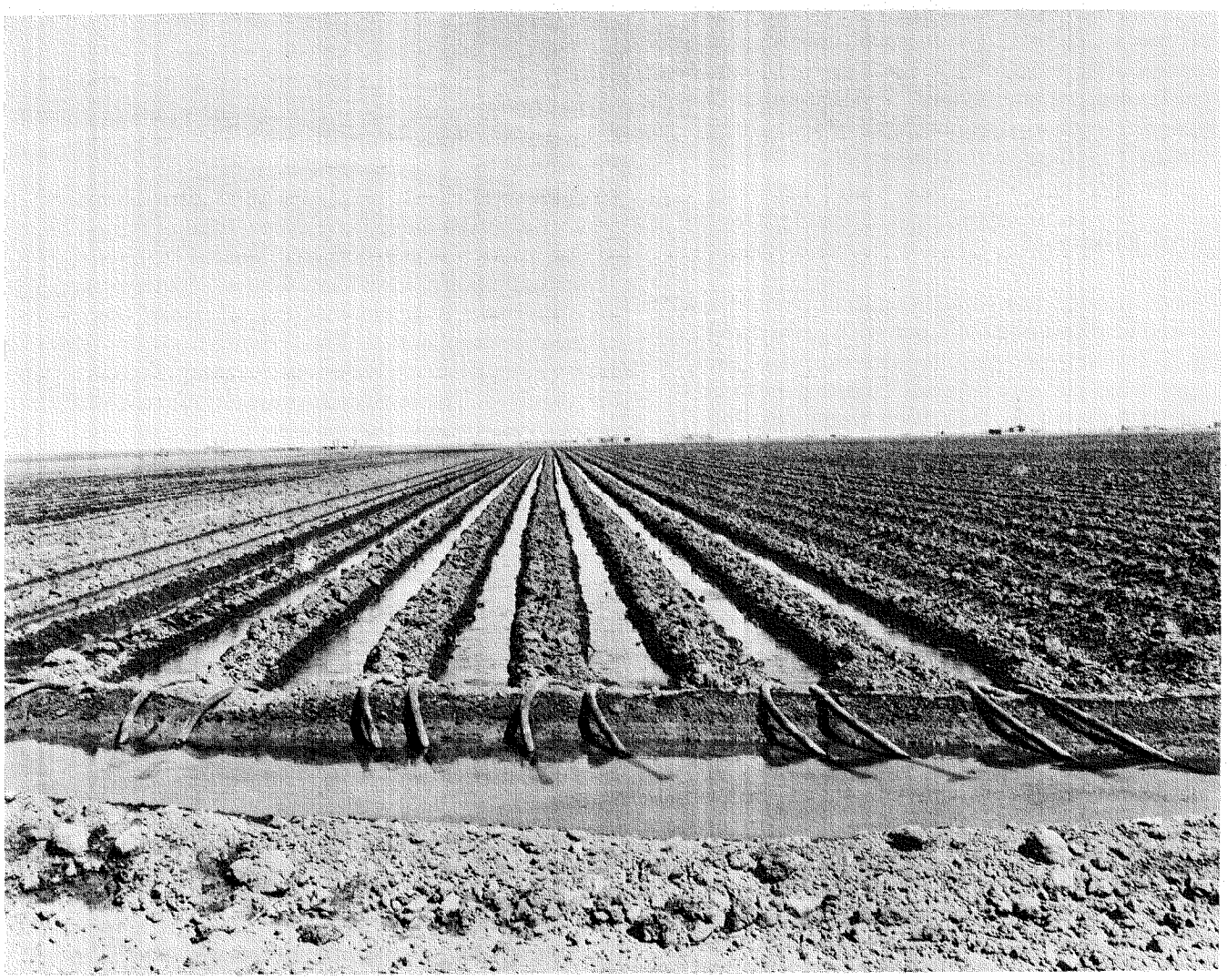


Figure 5–2.—Level furrow irrigation.

water between furrows (fig. 5–3). This method is best suited to sites where land slopes are at least 0.1 percent but no more than 3 percent in arid areas and no more than 2 percent in semiarid areas, 1 percent in subhumid areas, and 0.5 percent in humid areas. On smooth, uniformly sloping fields with slopes of 3 percent or less, crops can be planted across the slope to reduce the furrow grade (fig. 5–4). Where the cross slope is such that there is danger of the furrows breaking, graded furrows can be used on graded benches built across the slopes. If these benches are used, they should be spaced to meet the round-trip width requirements of the row-crop equipment to be used. For example, spacing should be in multiples of eight rows if four-row equipment is used. If the slope is not uniform in one direction, the benches may have one or more turns. To permit turning large equipment, the turn angles should not exceed 30 degrees. The turns in adjoining benches should be along the same radii path to eliminate the need for irrigating point rows (fig. 5–5). The cross slope within the benches should normally be as flat as practicable and should not exceed the 3 percent limitation.

Advantages

Graded straight furrows can be used with both large and small irrigation streams by adjusting the number of furrows irrigated at any one time to fit the available flow. Therefore, any method of water delivery from continuous flow to full demand can be

Figure 5-3.—Graded straight furrows.

accommodated. Where surface drainage is needed, the furrows act as channels to carry the excess surface water to safe disposal areas. Application efficiency can be high if proper recovery systems or cutback principles are used.

Limitations

Labor requirements are high unless the system is automated. Flow into each furrow must be carefully regulated to achieve uniform water distribution and minimum waste. Fields must be carefully leveled and facilities for collecting and disposing of surface runoff must be provided. Small irrigations especially needed for seed germination or for shallow-rooted crops are difficult to apply efficiently. Uniform application is difficult on soils with high intake rates. Land slopes must be relatively flat and uniform to permit installation within design limitations.

Graded Contour Furrows

Graded contour furrows are small graded irrigation channels on fields with uneven or warped surfaces where it generally is not practical to use straight furrows within permissible grade limitations (fig. 5-6). The furrows are curved to fit the general contour of the land and have enough grade to carry the irrigation stream to the end of the furrow. The grade must be somewhat variable to prevent creating

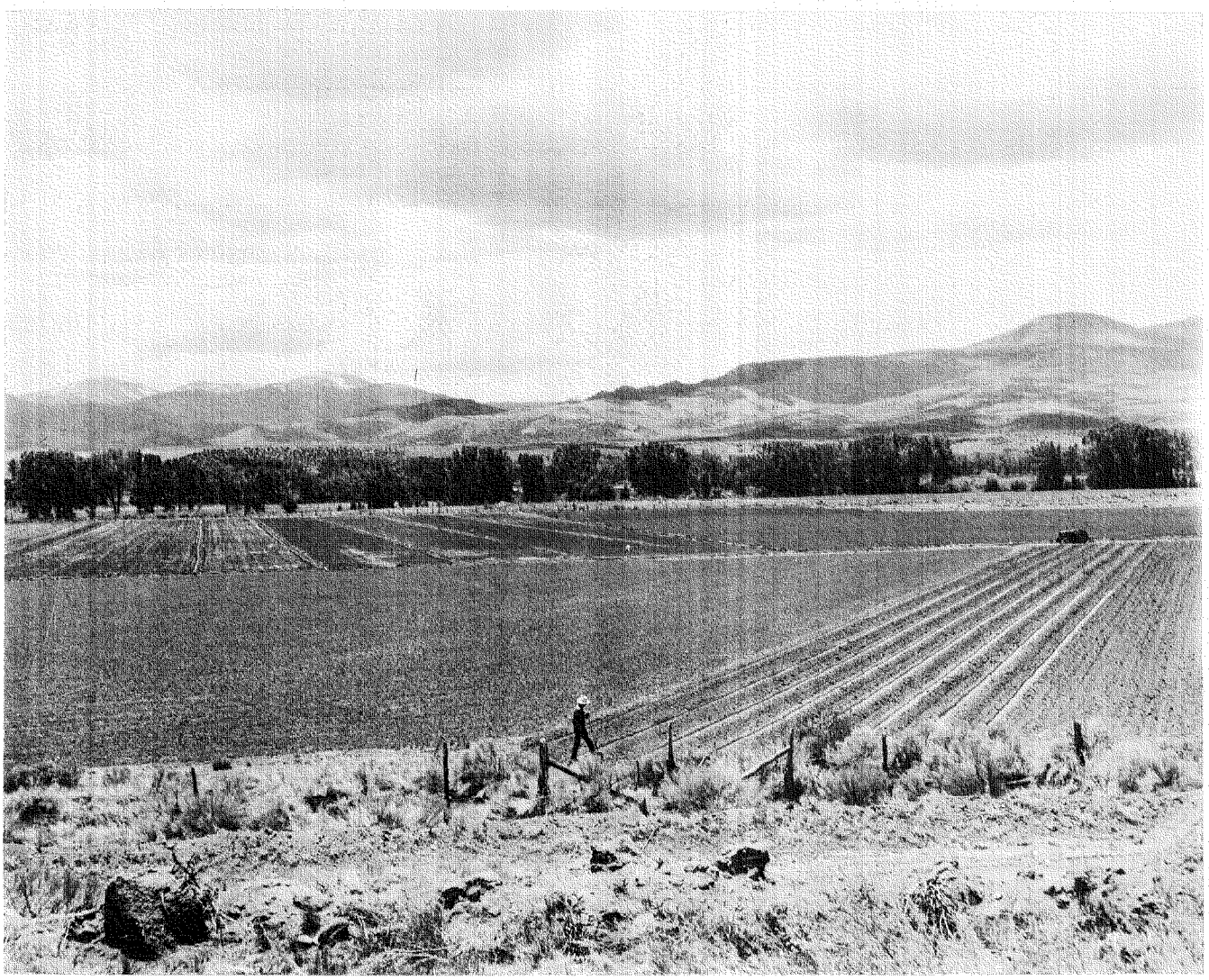


Figure 5-4.—Graded straight furrows across the slope.

numerous point furrows. Water application principles, including requirements for reuse or safe disposal of runoff, are the same as for graded straight furrows. Frequently, disposal systems require structural protection as a safeguard against water erosion.

Adaptability

The graded contour furrow method can be used on most moderately sloping fields and on most soils except sandy soils and soils that crack badly when dry. The ridges between furrows in sandy soils tend to break down or wash out, destroying the furrow and creating channels directly down the slope. Soils that crack provide channels for water, causing similar downslope furrow breaks. The graded contour method is particularly suited to fields of uniform slope in two directions because most of the furrows can be aligned across the slope. This method can be used for nearly all cultivated crops planted in rows. In arid or semiarid sections, deep-furrowed row crops on medium- or fine-textured soils can be irrigated if the land slope does not exceed 5 percent. On the coarser textured soils, the land slope must not exceed 4 percent because of the danger of furrow breaks. Maximum land slopes in semihumid areas should be approximately 1 percent less than those discussed above. Graded contour furrows are generally not recommended for humid areas. Land with slopes of up to 6 percent can be irrigated by this

Figure 5-5.—Benches to support furrows on sloping fields.

method if the furrows are supported by a system of parallel terraces. A parallel terrace system requires enough land leveling to ensure a continuous furrow grade. The terraces should be spaced to provide complete round trips with the farm equipment to be used.

Advantages

The graded contour furrow method can be used to safely irrigate land too steep for downhill furrows. Other advantages are the same as for straight graded furrows.

Limitations

Water delivery ditches frequently must be built on erosive grades that require structural protection or use of pipelines. Distribution to individual furrows from the head ditch is difficult. Tailwater-pickup systems normally have an erosive grade and require structural protection to provide stability. Considerable time is necessary to lay out a field; planting and tillage require considerable care. The irrigator must carefully guard against furrow overflow and washout. Grassed waterways and structures are usually needed to carry tailwater down the slope. Deep, large-capacity furrows must be built and maintained throughout the irrigation season. Rodent control is needed to prevent cross breakage and the flow of water from higher into lower furrows.

Figure 5–6.—Graded contour furrows.

Corrugations

Corrugations are small, closely spaced irrigation channels used to irrigate close-growing crops on moderately steep land (fig. 5–7). Irrigation water does not cover the entire field but is applied in small channels or corrugations evenly spaced across the field. Corrugations generally must conform to the slope of the land because of the small capacity of the water channels. For this reason level or graded contour corrugations are not recommended as a method for applying irrigation water. Corrugation irrigation is commonly considered a temporary method of water application to be used for the first irrigation on fields that later will be irrigated by the border method or as a method of spreading water in graded borders. However, corrugation irrigation as described in this chapter is a permanent system designed to apply water uniformly and efficiently. For efficient irrigation by the corrugation method, land slopes must be uniform and the water applied according to an irrigation water management plan. The length of time that water must flow in the corrugations varies with the amount of water required to refill the root zone and the intake rate of the soil. The rules governing the flow of irrigation water in graded furrows apply also to corrugations. Flow at the beginning of the irrigation should be as large as can safely be carried in the corrugations without causing erosion. Because of the small flows

Figure 5–7.—Corrugation irrigation.

used, cutting back the flow after water advances to the end of the furrow is usually not feasible. Therefore, facilities for recovery or safe disposal of tailwater are essential.

Adaptability

Corrugation irrigation is best suited to areas of moderately low rainfall and smooth fields with land slopes of between 1 and 4 percent. The use of corrugation furrows in humid areas usually creates a serious erosion hazard and, therefore, is not recommended. Except for those grown in ponded water, all close-growing, noncultivated crops such as legumes, grasses, and small grains can be irrigated by this method. Corrugation furrows are best suited to soils of fine to moderately coarse texture. They are not suitable for coarse-textured, high-intake-rate, or saline soils. The method is especially good for irrigating soils that tend to bake or crust, since only a small part of the surface is wetted.

Advantages

Close-growing crops can be irrigated efficiently if proper water management practices are followed. Corrugations can be constructed and maintained with commonly available tillage implements. Land preparation costs are relatively low, and irrigation streams can be large or small according to the available water supply.

Limitations

Labor requirements are high. Irrigation streams must be carefully regulated for uniform water distribution and minimum water loss. Fields must be corrugated at least once every year and, in many cases, more often. Equipment operating costs are also high, because the rough field surface is difficult to cross. The method is not well suited to slopes of less than 1 percent or to high rainfall areas because of the erosion hazard.

The application of water by furrows or corrugations appears to be a simple method. If efficient uniform water application is to be obtained, however, the systems must be properly designed, installed, and operated according to certain established criteria.

Before the specific design units can be selected, many determinations must be made in regard to soils, crops, topography, size, and shape of irrigable areas; farm equipment; and the farmer's personal preferences and operational practices. The designer must know the intake characteristics of each major soil type for placement in the proper design group. The crops to be grown and the available-water-holding capacity of the soils determine the normal design depth of application and whether furrows or corrugations are to be used.

The topography of the field determines the direction of irrigation and, in many cases, the grade of the corrugations or furrows and the appropriate lengths that will fit individual field boundaries. The farm equipment to be used determines the spacing and the maximum capacity that can be expected. The farmer's operational practices affect whether a cutback, tailwater recovery, or reuse or tailwater disposal system should be planned and what irrigation operating schedules will meet his needs.

The size of furrow stream and the time of application are both influenced by the operational method of water application to be used. If cutback-inflow operations are to be used, the design must be based on two different sizes of furrow streams, and these require a specific procedure and time of application. If the impoundment method is used, the application time will be relatively short and the application rate correspondingly high.

A continuous stream with reuse facilities will have a different design than either of the other operations methods. Above all, the selected design and layout must meet the owner's approval if the system is to operate satisfactorily. The selected design will be for a normal irrigation application, but adjustments for application depth, time of application, and furrow flow rate for specific irrigations may be needed during the season.

Land Preparation

Efficient irrigation is most easily accomplished on land with uniform topography. If the area to be irrigated can be divided into uniform operational segments, a single set of furrow or corrugation design criteria and operational procedures can be used. Since neither soil nor topography is normally uniform over large areas, it is generally advisable to divide fields into design areas according to soil uniformity and do the land leveling needed to develop uniform land slopes within the limitations imposed by the design criteria. For uniform operation of a furrow or corrugation system, each furrow or corrugation within a design segment should have the same length and grade. To obtain uniform furrow length, the segment must have parallel sides of uniform length, and to obtain uniform grade, the surface must conform to a plane. (See SCS National Engineering Handbook, Section 15, Irrigation; Chapter 12, Land Leveling.)

Layout and Construction

The design of an irrigation system sets the limits for the system on an individual farm or field. The design criteria specify the inflow rate for the design length of furrows on a predetermined grade on a soil characterized by a given intake family. A number of points must be considered when selecting the design or designs to be used on an individual farm. An irrigation system layout should be based on the following items as they relate to a specific field or fields.

Fields of workable size and shape are important to successful irrigation farming. Unless a system is carefully laid out, some areas may not receive irrigation water, or may be virtually inaccessible and useless to the farm enterprise. Sharp turns or acute angles must be avoided. Fields should be as nearly rectangular as possible. Furrows or corrugations in any field should be as nearly equal in length as is practicable to obtain. Irrigation in adjoining fields generally should be in the same direction or at right angles. Water application is normally difficult if irrigations in adjacent fields are in opposite directions. Permanent surface features such as power lines, buildings, structures, and other obstructions influence the field shape that can be used or the division to be made between fields. The cropping pattern to be followed is also a determining factor in field layout.

A good soil map is essential in the layout of any irrigation system. Where soils have appreciable differences in intake rate and water-holding capacity, the fields should be divided as nearly along soil boundaries as is practicable and provide uniform row lengths. The outlet end of the rows can cross the boundary between a slow intake rate soil and a somewhat higher intake rate soil and still permit efficient application. Crossing the boundary between a high intake rate soil and a lower intake rate soil for any appreciable distance should be avoided.

The need for a field road system is frequently overlooked in laying out an irrigation system. As a result, that part of the farm is inaccessible to farm machinery, the system is damaged by travel of equipment, or the roads are impassable after an irrigation or a rain. For the operation of the system, roads should be provided above the field head ditches or mains and below field drains. The following points should be considered in the layout of a farm road system:

1. Ease of operating the water-distribution system.
2. Ready access to all areas of the farm for farm equipment.
3. Transportation of farm produce from the fields.
4. Dryness and usability of roads.
5. Requirements for farm-crossing structures.

Erosion Control

The furrow system must be designed to avoid conditions that would contribute to soil erosion. Serious erosion can occur without any soil being removed from the field. In surface methods of irrigation, the irrigating streams are largest and most erosive where they first enter the field. As the streams progress toward the lower end of the field, they are reduced by the amount of water infiltrated into the soil. The accumulated sediment load also reduces their erosivity. Often the streams erode the soil at the upper end of the field but have insufficient carrying capacity at the lower end to transport material from the field. About the only characteristic that erosion under furrow irrigation and erosion under rainfall have in common is that each is caused by flowing water. In most other respects they are diametrically opposite. Under irrigation, the amount of erosion depends on the condition in the furrow and

not on the overall condition of the field. It matters very little whether the area between the furrows is vegetated or bare, compacted or loose. The specified limitations for land slope, furrow length and grade, and stream size should ensure that erosion from the water application system is within allowable limits.

Soil Water Intake Characteristics

The water intake rate of a soil is the most important item to be considered in the design of a furrow or corrugation system. The higher the intake rate, the larger the inflow rate and the shorter the application time should be. Furrows and corrugations, in contrast to borders or sprinkler systems, depend on both vertical and lateral transmission of the applied water to obtain the needed intake. A number of factors influence intake and make it especially difficult to set specific design limits for furrow systems. Among them are: (1) physical features of the soil, (2) cultural practices used, (3) cropping practices, (4) soil water level at time of irrigation, (5) water quality, and (6) previous irrigations during the irrigation season.

Physical Features of Soil

The major soil physical characteristics that affect the water intake rate are the texture, structure, and tilth. Because the texture of a soil changes very little, the intake rate of a specific soil can be determined if farming practices are used that do not materially change soil tilth. Generalized intake equations as related to intake-family groups for various kinds of soils are given in a later section of this chapter. Tests to determine the placement of an individual soil into one of these family groups are described in the Evaluation section.

Cultural Practices

Tillage practices can greatly increase or decrease the water-intake rate of soils, depending on the equipment used and the moisture condition of the soil at the time the tillage is performed. Subsoiling or deep chiseling of a soil breaks up plowpans and fractures other very slowly permeable horizons, thereby increasing the capacity of the soil to take in water as long as the artificially increased porosity remains. The effect of this tillage disappears by the second or third irrigation. Listing or other tillage that leaves the soil loosened also produces a temporary increase in soil intake rates. In contrast, tillage of wet soils causes the soil to compact and form plowpans that may permanently reduce intake. Intake rates are also reduced in furrows compacted by tractor wheels. Furrow intake rates are often purposely reduced on sandy soils to allow longer runs and longer time of sets by pulling a drag or other smoothing and compacting implement down the furrows in which water is to be applied.

Cropping Practices

Intake rates can be increased by incorporating crop residues evenly into the first few inches of the soil surface layer. This practice also helps prevent surface puddling of the soil, which can reduce soil intake to almost zero. A higher content of relatively large aggregates of soil particles and greater water-intake capacity generally result from good crop rotation practices.

Soil Water Level

The intake rate of a wet soil is slower than that of a dry soil. Intake results from a combination of soil tension or suction, and gravitational pull. The tensional force is the difference in tension between the wetted front and the adjoining dry area. Therefore, this force decreases as soil water content increases. Tests show that a soil with 80 percent available water has an intake rate of approximately 70 to 80 percent of that for a soil with 60 percent available water. In contrast, the wetting front advances more rapidly when the soil is wet because less water is needed to saturate the soil. Thus, the effect of initial wetness can be significant during early stages of infiltration but decreases with time and eventually tends to vanish.

For maximum crop production, adequate water should be available at very low tension so that the root system can easily withdraw as much soil water as the plants can use. The response of a crop to different soil-water levels varies according to the crop's growth characteristics and its inherent ability to obtain water under changing tensions. High soil water levels are especially important for such crops as potatoes, particularly at critical growth periods such as the fruiting stage. Salts in the soil solution are also a factor in determining the optimum water level. The higher the concentration of salts in the soil solution, the higher the available water level that

must be maintained. Generally, the level of readily available water in the major root zone of a soil should be maintained above 50 percent. Where practical to do so, the level of readily available water of a silty clay soil should be maintained at 60 to 75 percent, whereas on a fine sandy loam, the water can be safely depleted to 35 to 40 percent before irrigation water is applied. The soil water level that is to be maintained is a factor in determining the design application depth and frequency of application.

Water Quality

Irrigation water contains dissolved materials that accumulate in soils. These materials may cause profound changes in water-intake characteristics. The material may be a kind of salt or a colloidal substance. Some of the dissolved salts, such as calcium and magnesium, may increase the intake rate of a soil, but an excess of sodium is very detrimental. Excessive sodium replaces the other cations attached to the soil particles, changing a calcareous soil to a sodic soil. A calcareous soil is aggregated, very granular, and permeable to water. Sodic soil is gelatinous, deflocculated, and nearly impervious to water. Colloidal materials generally are clay particles that may also decrease soil intake rates.

Seasonal Variation

The intake rate of a soil in a furrow or corrugation irrigation system normally becomes progressively less for each irrigation during the season, with possibly the exception of the last irrigation. Then crop residues or growing plants tend to accumulate in the water channels, restricting water flow and increasing intake.

In colder climates, heaving of soils during the winter produces more voids. But as farming operations are conducted, the soils settle back and become more compact. Spring plowing loosens the soil surface, allowing increased intake during the initial irrigation. As the season progresses, however, this loosening effect disappears unless the soil is cultivated during the season. An example of the seasonal change in intake rates measured at Grand Junction, Colo., is shown by the following data:

Date:	*Average intake rate* [1]
June 5	0.083
July 2	.138
Aug. 5	.126
Aug. 26	.100
Sept. 9	.126

[1] Inches per hour

The design must be such that inflow rate and application time can be adjusted readily during the season without changing the furrow layout.

Distribution of Intake

Knowledge of the wetting pattern—the shape of the wetted bulb in the soil beneath the surface—is needed for designing the system. The uniformity of the soil greatly affects both the intake rate of a soil and the shape of the wetted bulb.

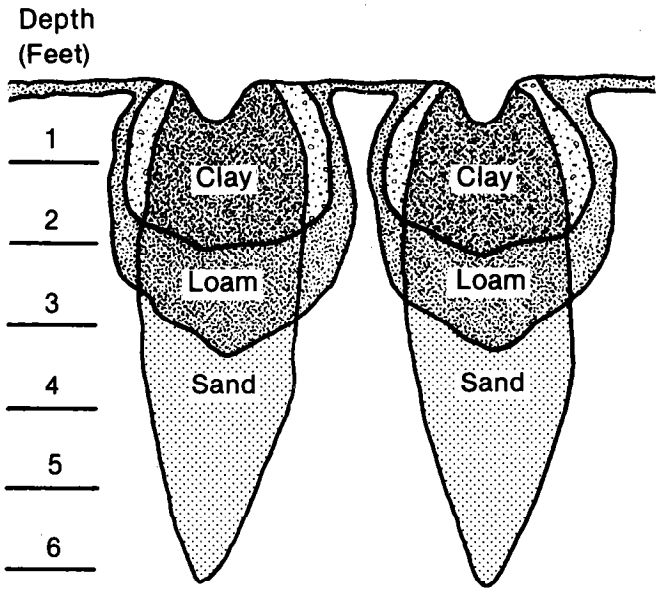
Wetted bulbs.—The designs in this chapter are based on the assumption that the wetted bulbs from adjacent furrows will overlap or nearly overlap by the time the desired application has been obtained. This assumption is valid if furrows are properly spaced according to soil intake and depth of water application. Where bulbs do not overlap furrow spacings should be adjusted so that they do overlap. It may be desirable to irrigate only alternate furrows. This practice provides storage for rainfall or for maximum use of the available irrigation water and intentionally irrigates only a percentage of the area between the watered furrows. In such cases, the design should be based on the width of area irrigated instead of the spacing between furrows.

Homogeneous soils.—Water intake in a homogeneous soil initially occurs in a radial pattern. The movement is almost as great outward as it is downward. The force responsible for this type of water movement is mainly soil tension. As the soil becomes saturated, tension force decreases and gravity force predominates. In homogeneous soils, the wetted bulb forms the shape of a parabola, with the horizontal and vertical intake relationship changing with increasing time of application. The lateral movement depends primarily on soil texture. Wetting patterns are broader in fine-textured soils than in coarse-textured soils (fig. 5–8).

Nonhomogeneous soils.—Soils with nonuniform profiles have greater lateral movement of water than soils with uniform profiles (fig. 5–9). Any deviation in the physical characteristics of a soil changes the wetted bulb pattern under furrow or corrugation irrigation. For example, a horizontal layer of coarse

Figure 5-8

Typical Patterns of Moisture Penetration by the Same Amount of Water from Furrows in Different Homogeneous Soils



material or a layer of finer material causes the parabolic wetted bulb to flatten and actually assists in obtaining a more uniform water application than is possible in a homogeneous soil. A large percentage of irrigated soils is layered in one of these fashions.

Spacing

Spacing affects the irrigation system in two ways. First, the spacing dictates the maximum capacity, which determines the maximum inflow rate. That, in turn, dictates the maximum furrow or corrugation length. Second, if spacing is such that the wetted bulbs do not overlap, the area between the rows receives only a partial irrigation.

Furrow Spacing

Furrow spacing must be compatible with the crop to be grown, the farm machinery to be used, and the lateral transmission of soil water in relation to vertical intake. For most field crops such as corn, cotton, or potatoes, the furrow spacing is the distance between crop rows and is selected to facilitate the use of planting, cultivating, and harvesting implements. Bedded crops such as lettuce, carrots, or onions may require furrows only between pairs of rows.

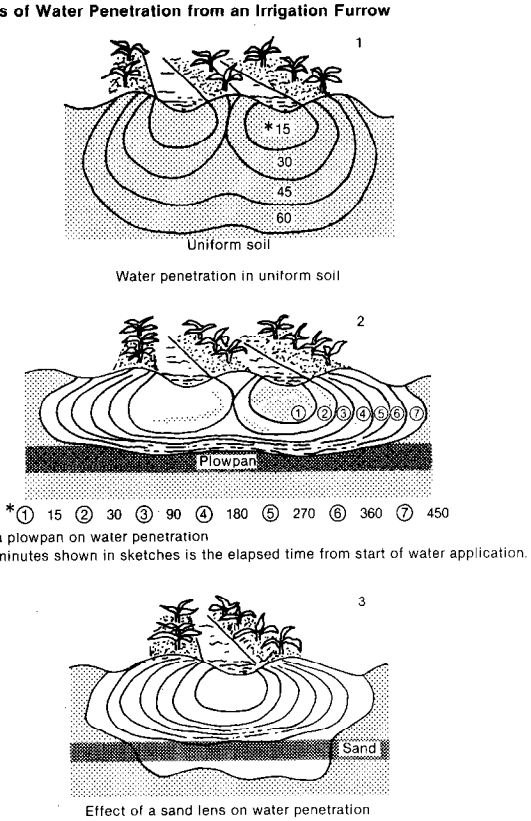
Normally an irrigator uses a standard width between furrows for a number of different crops to make use of the same planting and cultivating equipment and frequently to facilitate the use of gated pipe for applying irrigation water. Regardless of the crop being irrigated, the furrow spacing must permit water moving laterally to meet between adjacent furrows within the time allotted for the gross application and before an appreciable amount of water penetrates below the root zone.

For most soils, spacing does not ordinarily present a problem unless water is applied to shallow depths, crops are planted on high beds, or alternate-row irrigation is used. The problem of obtaining adequate lateral spread is especially severe where these conditions are compounded by irrigation grades steep enough to limit the depth of flow in the furrows.

Flat irrigation grades permit the use of furrow streams with deeper flow, a greater wetted perimeter, and corresponding wider spacing of furrows. If the soil is relatively dry before the

Figure 5-9

Examples of Water Penetration from an Irrigation Furrow



irrigation is applied, wetting patterns can be determined by using a soil-water probe. Examination of a number of furrows in which water has been applied for different periods of time is usually the best way to determine the maximum furrow spacing for any particular soil.

Corrugation Spacing

The spacing of corrugations also depends on how rapidly water moves laterally through the soil. Because they are generally independent of crop spacing, corrugations can be spaced readily according to the soil intake characteristics, the depth of irrigation desired, and the corrugation grade to be used. They generally can be farther apart on fine-textured soils than on coarse-textured soils and closer on steep slopes than on flat slopes. Table 5-1 can be used in selecting corrugation spacings.

TABLE 5-1.—*Maximum corrugation spacing (inches)*[1]

Depth of irrigation application	Soil intake family		
	0.1 to 0.4	0.5 to 0.9	1.0 to 2.0
Inches:			
2	18	15	12
3	20	18	15
4	22	20	18
5	24	22	20

[1]If the corrugation grade is 2 percent or less, spacing can be increased to the next wider spacing, such as from 15 to 18 or from 22 to 24 inches.

Equivalent Intake

Intake from furrows where only part of the soil surface is in contact with water is measured in volume, e.g., cubic feet per foot of furrow length. This volume measurement is irrespective of furrow spacing. The depth of irrigation application needed on a specific area is usually expressed in inches. If application depth is expressed in inches, spacing is of utmost importance. Cubic feet per foot of length can be converted to equivalent inches of water depth for the area irrigated by use of the equation:

$$\text{Equivalent inch depth} = \frac{144 \times \text{ft}^3 \text{ per ft}}{\text{furrow spacing in inches}}$$

It can readily be seen that, for a given volume of intake, a furrow spacing of 48 inches would have an average application depth of one-half as many inches as would a furrow spacing of 24 inches (table 5-2).

Table 5-2.—*Conversion—cubic feet per foot of furrow to inches of equivalent depth*

(Ft³/Ft)	Furrow or corrugation spacing (inches)							
	18	20	22	24	30	36	40	48
0.05	0.40	0.36	0.33	0.30	0.24	0.20	0.18	0.15
.10	.80	.72	.66	.60	.48	.40	.36	.30
.15	1.20	1.08	.98	.90	.72	.60	.54	.45
.20	1.60	1.44	1.31	1.20	.96	.80	.72	.60
.25	2.00	1.80	1.64	1.50	1.20	1.00	.90	.75
.30	2.40	2.16	1.96	1.80	1.44	1.20	1.08	.90
.35	2.80	2.52	2.29	2.10	1.69	1.40	1.26	1.05
.40	3.20	2.88	2.62	2.40	1.92	1.60	1.44	1.20
.45	3.60	3.24	2.95	2.70	2.15	1.80	1.62	1.35
.50	4.00	3.60	3.27	3.00	2.40	2.00	1.80	1.50
.55	4.40	3.96	3.60	3.30	2.64	2.20	1.98	1.65
.60	4.80	4.32	3.93	3.60	2.88	2.40	2.16	1.80
.65	5.20	4.68	4.25	3.90	3.12	2.60	2.34	1.95
.70	5.60	5.04	4.58	4.20	3.36	2.80	2.52	2.10
.75	6.00	5.40	4.91	4.50	3.60	3.00	2.70	2.25
.80	6.40	5.76	5.24	4.80	3.84	3.20	2.88	2.40
.85	6.80	6.12	5.56	5.10	4.08	3.40	3.06	2.55
.90	7.20	6.48	5.89	5.40	4.32	3.60	3.24	2.70
.95	7.60	6.84	6.22	5.70	4.56	3.80	3.42	2.85
1.00	8.00	7.20	6.55	6.00	4.80	4.00	3.60	3.00
1.10	.....	7.92	7.20	6.60	5.28	4.40	3.96	3.30
1.20	.....	.....	7.85	7.20	5.76	4.80	4.32	3.60
1.30	.....	.....	.....	7.80	6.24	5.20	4.68	3.90
1.40	.....	.....	.....	.....	6.72	5.60	5.04	4.20
1.50	.....	.....	.....	.....	7.20	6.00	5.40	4.50
1.60	.....	.....	.....	.....	7.70	6.40	5.76	4.80
1.70	.....	.....	.....	.....	8.16	6.80	6.12	5.10
1.80	.....	.....	.....	.....	.....	7.20	6.48	5.40
1.90	.....	.....	.....	.....	.....	7.60	6.84	5.70
2.00	.....	.....	.....	.....	.....	8.00	7.20	6.00

Shape

Furrows and corrugations are constructed in a number of different shapes, depending on the crop to be grown and type of equipment used. The shape or cross section is one of the features that determine flow capacity as well as the area of soil that is in contact with the flowing water. The shape is determined by the equipment used in constructing the channels and is modified by subsequent tillage, growing vegetation, and flowing water.

Furrow Shape

The furrow cross section must be large enough to contain the largest irrigation stream to be introduced without overtopping and to contain the runoff resulting from expected rainstorms. Soil from the ridges tends to partially fill the furrows and, as the growing season progresses, the depth and area of the channels usually decrease. Allowances should be made for such decreases when the furrow capacity is determined.

Furrow shape is modified by the water as it moves down the slope. On steep slopes the water tends to form a narrow channel, whereas on flatter slopes it forms a broad channel. These tendencies are greater on sandy soils than on clay soils.

Many different furrow system designs would be necessary if one were made for each of the many furrow shapes used. Most furrows constructed between rows of cultivated crops are either parabolic or trapezoidal (shallow, flat bottoms). Field observations indicate few differences between these two furrow shapes for design purposes. Therefore, designs in this chapter are based on a trapezoidal furrow. Although the actual furrow cross section may be considerably different, the effect on flow and intake characteristics is not significant enough that other cross sections need to be considered in developing furrow designs. As previously discussed, the furrow cross section must be adequate to contain the planned furrow stream. Table 5-3 can be used in estimating the required furrow cross section for various furrow streams.

TABLE 5-3.—*Required furrow cross-sectional area in square feet*

Furrow grade (ft/ft)	Furrow stream (gpm)						
	50	40	30	25	20	15	10
Level [1]	0.70	0.59	0.48	0.42	0.35	0.25	0.21
0.0005	.38	.32	.26	.23	.19	.14	.11
0.0010	.29	.25	.20	.17	.15	.11	.09
0.0020	.23	.19	.15	.13	.11	.08	.07
0.0040	.17	.15	.12	.10	.07	.06	.05
0.0075	.....	.....	.....	.....	.06	.05	.04
0.0100	.....	.....	.....	.....	.....	.04	.04

[1] Level furrow cross sections were calculated by using S=0.0001.

The furrow cross section plus the furrow grade also determine the volume of water in channel storage during an irrigation. Table 5-4 gives an estimate of this storage.

TABLE 5-4.—*Furrow storage in gallons per foot length* [1]

Furrow grade (ft/ft)	Furrow stream (gpm)						
	50	40	30	25	20	15	10
Level	5.24	4.43	3.57	3.11	2.63	1.90	1.56
0.0005	2.85	2.41	1.94	1.69	1.43	1.03	.85
0.0010	2.20	1.86	1.50	1.30	1.10	.79	.65
0.0020	1.69	1.43	1.15	1.00	.85	.61	.50
0.0040	1.30	1.10	.89	.77	.65	.47	.38
0.0075	.....	.....	.....	.....	.51	.39	.30
0.0100	.....	.....	.....	.....	.....	.33	.27

[1] The average storage for a furrow reach is approximately 80 percent of these values.

Corrugation Shape

Corrugations are seldom more than 0.10 square foot in cross-sectional area unless they are formed by lister-type equipment. They vary widely in shape because of the numerous tools used to construct the channels. Among the implements used are lister bottoms with the wings cut off to provide a water channel without high beds, lister bottoms followed by a drag to flatten the beds, corrugating shovels, wooden-sled-type corrugators with sharpened runners, and round metal pipes mounted as runners similar to the wooden-sled type. Most of these implements construct small channels that have cross-sectional shapes of about 0.2-foot bottom width and 1:1 side slopes.

A Manning's roughness coefficient value of 0.10 for drilled crops is commonly used for design purposes. This higher retardance value means that the capacity of corrugations is about 40 percent of that for furrows of equal cross-sectional area.

Grade

The grade of a furrow or corrugation irrigation system should be slight enough that soil loss from either rainfall runoff or irrigation streams is kept within allowable limits. Conversely, grade should be adequate to provide surface drainage where needed to prevent waterlogging the soil.

Furrow Grade

Furrow grade should generally be 1 percent or less. In arid areas where erosion from rainfall is not a problem, the grade can be as much as 3 percent. In humid areas, furrow grade usually should not exceed

0.3 percent, but up to 0.5 percent may be safe if runs are short enough to prevent accumulation of runoff water that would cause soil erosion. The maximum length of a run can be determined by the procedure given under furrow length. In arid and semiarid areas, the minimum grade can be a zero if the planned crop allows impoundment of water around the root system. In humid and subhumid areas, a minimum grade of 0.05 foot per 100 feet should be provided to ensure surface drainage. The cross slope, the slope perpendicular to the direction of irrigation, must be limited to that which will not result in either irrigation water or storm runoff overtopping the ridges. Cross slope for furrows with grades of 0.5 percent or more should be limited to 1 percent or to the furrow grade, whichever is the lesser, unless the furrows are supported by benches or by terraces.

Wherever practical, the furrow grade should be uniform. Under certain conditions, however, it may be desirable to use variable furrow grades, if the steepest grade is not more than twice the flattest slope. To obtain reasonably uniform application of water, the furrows should have grades that vary in one direction only. They may increase or they may decrease, but they should not do both. Reverse grades are not permissible. The maximum recommended furrow grade for erodible soils can be calculated by the formula: $S_{(max.)}=(P_{30})^{-1.3}$, where P_{30} is the 30-minute rainfall on a 2-year frequency and S is the furrow grade in percent (fig. 5–10). A solution to the above formula follows:

30-min rainfall (inches)	Maximum furrow grade (percent)
0.4	3.3
.6	1.9
.8	1.3
1.0	1.0
1.2	.8
1.4	.65
1.6	.55
1.8	.50

Less erodible soils may exceed these limits by approximately 25 percent.

Corrugation Grade

Corrugations are aligned in the direction of the steepest slope and are recommended only on slopes of 1 to 4 percent.

Length

The length of a furrow or corrugation system is in direct proportion to the size of furrow or corrugation stream applied. The maximum length is generally based on the maximum nonerosive furrow stream or the capacity of the furrow, whichever is less.

Furrow Length

The optimum furrow length is the longest length that permits efficient water use, accumulates no greater quantities of storm runoff than can be accommodated without erosion or overtopping, and provides adequate drainage. Long furrows are more efficient because they require fewer turns for farm equipment. Several factors place limitations on length of run. The more important of these are: (1) intake rate of the soil; (2) grade of the furrows; (3) rainfall intensity; (4) depth of application; (5) field dimensions; and (6) location of soil boundaries. Other factors being equal, furrows must be much shorter on coarse-textured soils with high intake rates than on fine-textured soils with low intake rates. The length of run also depends on the water inflow rate to the furrow. Since the grade of the furrow, for the most part, determines the maximum nonerosive furrow stream that can be applied, it necessarily places a limit on the length of run. Steep grades require shorter lengths of run than do flatter grades.

In removing storm runoff, each furrow acts as a channel with a drainage area equal to the furrow spacing multiplied by its length. Runoff is collected throughout the length of the furrow, and the flow becomes progressively greater down the furrow. If no limitation is placed on the length of the furrow, the rainfall-runoff stream will become large enough to erode or overtop the furrow. The volume of runoff in the furrow is determined by the intensity of rainfall and the area of drainage. Because the furrow length is the only factor that can be controlled, it must be limited to prevent erosion and overtopping. The furrow stream from rainfall runoff can be determined by calculating the runoff expected from a 6-hour, 2-year frequency storm (fig. 5–11). The hydrograph from this storm can be considered as a rectangular hydrograph and the average furrow flow calculated. Tables 5–5, 5–6, and 5–7, and figures 5–11 and 5–12 can be used in determining the maximum furrow length as governed by rainfall intensity.

Figure 5-10

2-Year, 30-Minute Rainfall (Inches)

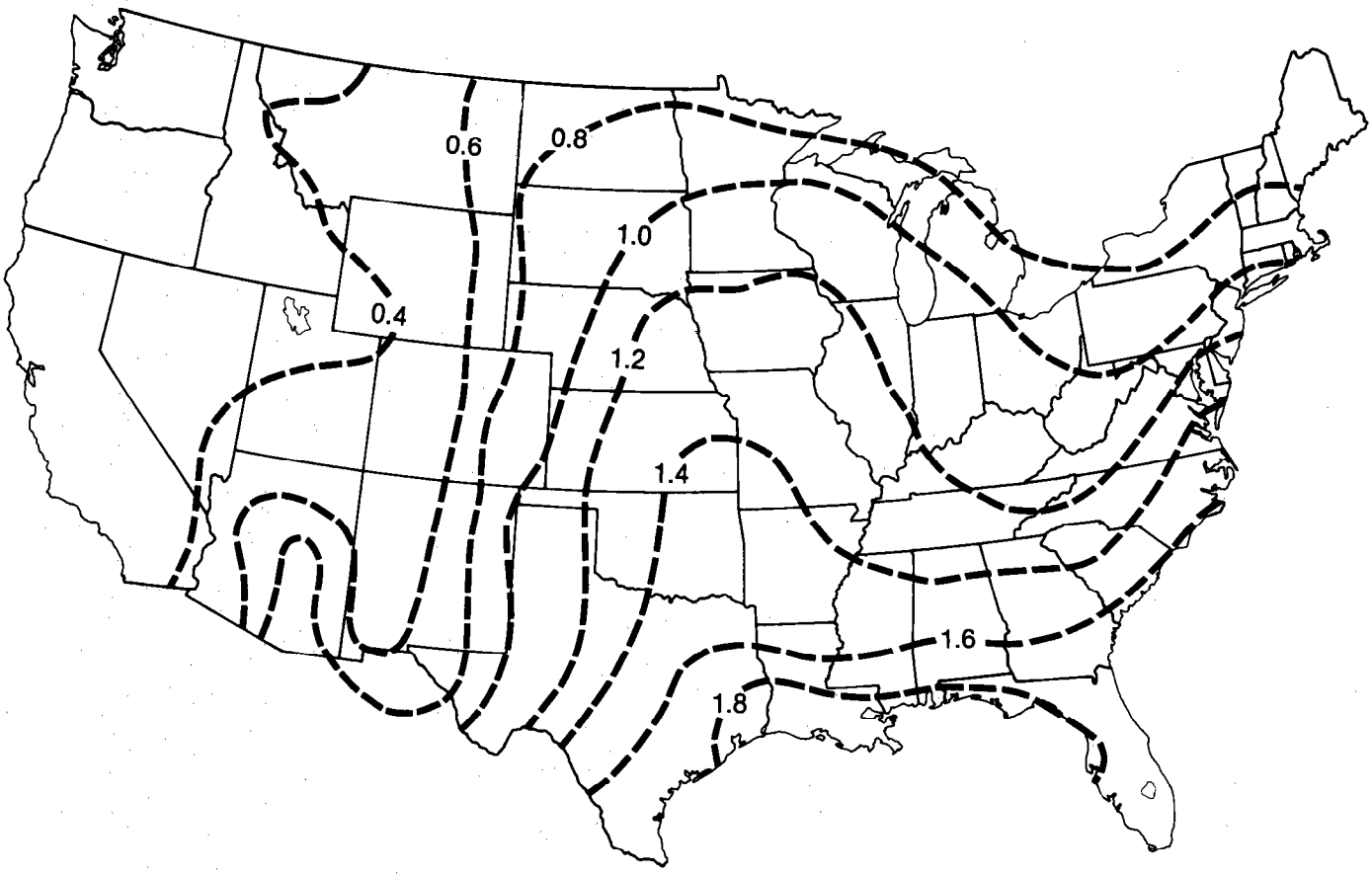


TABLE 5-5.—*Runoff for inches of rainfall*

	Curve No. 75 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
1	0.03	0.05	0.07	0.10	0.13	0.16	0.20	0.24	0.28	0.33
2	0.38	0.43	0.48	0.53	0.59	0.65	0.71	0.77	0.83	0.89
3	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.52	1.59
4	1.67	1.74	1.82	1.89	1.97	2.04	2.12	2.20	2.82	2.36

TABLE 5-6.—*Runoff for inches of rainfall*

	Curve No. 80 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05
1	0.08	0.11	0.15	0.19	0.24	0.29	0.34	0.39	0.44	0.50
2	0.56	0.62	0.68	0.75	0.82	0.89	0.96	1.03	1.10	1.17
3	1.25	1.33	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96
4	2.04	2.12	2.20	2.29	2.38	2.46	2.55	2.63	2.72	2.81

Figure 5-11

2-Year, 6-Hour Rainfall (Inches)

TABLE 5-7.—*Runoff for inches of rainfall*

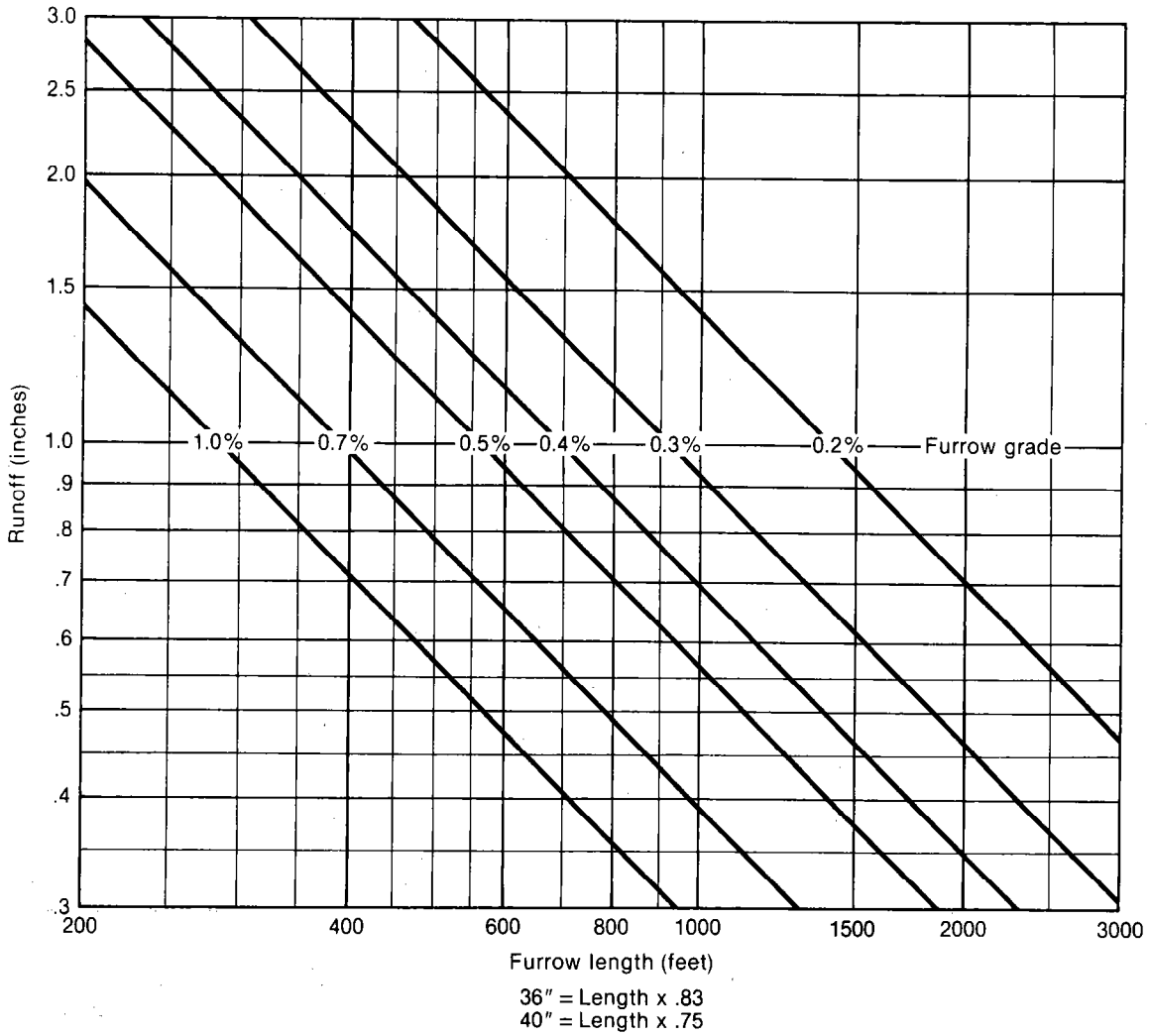
	Curve No. 85 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13
1	0.18	0.22	0.28	0.33	0.39	0.45	0.52	0.59	0.65	0.73
2	0.80	0.87	0.95	1.02	1.10	1.18	1.26	1.34	1.42	1.51
3	1.59	1.68	1.76	1.85	1.93	2.02	2.11	2.10	2.28	2.37
4	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.19	3.28

Example: Determine furrow length on a 0.3 foot per 100 feet grade at Sikeston, Mo., for a soil in hydrologic group 75. Furrow spacing is 36 inches. Solution: From figure 5-11, the 2-year, 6-hour rainfall is 2.7 inches. From table 5-5, runoff is 0.77 inch. From figure 5-12, maximum length for 30-inch furrows is 1,250 feet. For 36-inch furrows, the length is $1{,}250 \times 0.83 = 1{,}040$ feet.

The length of furrow may also be limited by the size and shape of the field. If the field length exceeds the maximum design furrow length, the field must be divided into two or more lengths. In selecting lengths, consider boundaries between adjoining soils that have appreciably different intake rates or water-holding capacity. For example, low intake rate soils located in the upper reaches of the furrow length can sometimes be included with soils having a higher intake rate. Design criteria describe the maximum furrow length that should be considered for efficient water application with various intake rates, furrow grades, and application depths.

Figure 5-12

Runoff From 2-Year, 6-Hour Frequency Storm
Maximum Length of Furrows on 30″ Spacing



Corrugation Length

Corrugation length is generally restricted by the combination of soil intake rate and the flow capacity of the corrugations. Water should reach the end of the corrugations in the time necessary to provide a uniform application. Design criteria in this section provide guidance in selecting the proper corrugation length.

Stream Size

The proper furrow or corrugation inflow rate depends on the furrow or corrugation length. Therefore, if a maximum length is to be considered, it is necessary to determine the maximum nonerosive stream size that can be used for each design segment of the irrigation system.

Furrow Stream

Furrow designs in this chapter relate the inflow rate to soil intake rate; furrow length, slope, and spacing; and the desired application depth. One of the major limiting factors in furrow design is the maximum stream size that can be used safely. The maximum allowable nonerosive stream depends on a number of factors, including the slope of the furrow, the furrow shape or capacity, and the erodibility of the soil. A common method of determining this maximum stream size is by use of the empirical formula, $Q = \frac{10}{S}$ where, Q = maximum

allowable stream in gallons per minute and S = slope of furrow in percent. This formula is independent of the furrow shape or the erodibility of the soil. A better criterion is to limit the velocity of the furrow stream according to the erodibility of the soil.

Soils may erode if the furrow stream velocity exceeds about 0.5 foot per second, whereas the less erodible soils may safely withstand velocity of 0.6 foot per second. Figure 5–13 shows velocity and depth of flow for various stream sizes and furrow grades in a standard shaped furrow. Where furrows are constructed with wide bottoms, the velocity would be less than indicated, and larger furrow streams can be used safely. If empirical formulas are used to determine the maximum furrow grade, $Q=\frac{10}{S}$ should be used for erodible soils, $Q=\frac{15}{S}$ for erosion-resistant soils, and $Q=\frac{12.5}{S}$ for average soils.

A practical upper limit for inflow rate is 50 gpm, regardless of furrow slope. Streams larger than 50 gpm usually require a larger cross-sectional area of furrow than the usual planting and tillage equipment provides.

Corrugation Stream

The capacity and grade of the corrugations determine the maximum stream size that can be used. Most corrugations do not accommodate an inflow rate much in excess of 10 gpm. If corrugations are to be constructed or opened before each irrigation, the same criteria should be used for maximum stream size as are used for furrows. If corrugations are such that the growing crop or crop residues retard water flow, the maximum nonerosive stream can be estimated by the formula $Q_{max} = \frac{40}{S}$; however, the corrugation capacity may be the limiting factor.

Methods of Water Control

The depth of irrigation water absorbed at a station along the furrow or corrugation length is proportional to the time that water is in contact with the station, the opportunity time. For uniform intake, opportunity time should be as nearly uniform as is practicable for each segment of furrow length. To meet this objective, three methods of water control are applicable: (1) reducing the inflow rate after water has advanced to the end of the furrow, (2) recirculating or recovering surface runoff, or (3) impounding the water in the furrow and eliminating surface runoff.

Cutback Inflow

The cutback method requires that the water be introduced rapidly so that the entire furrow length is wetted in a minimum time, and then the size of the furrow stream reduced so that it is approximately equal to the intake rate of the soil. This method should be carefully considered for use in furrow irrigation because it requires a minimum use of power. If the cutback furrow stream is to be used, the method must be made practical to follow by developing an irrigation schedule that will fit normal farm operation or by automating the system. The following guidelines provide a practical procedure for using the cutback-inflow method:

1. The initial furrow stream should be applied until the water has advanced to the end of the furrow.
2. The inflow rate should then be reduced to one-half the initial rate.
3. The reduced inflow rate should be applied until the design application depth is reached.
4. Provisions should be made for storage, disposition, or recovery of the runoff water.

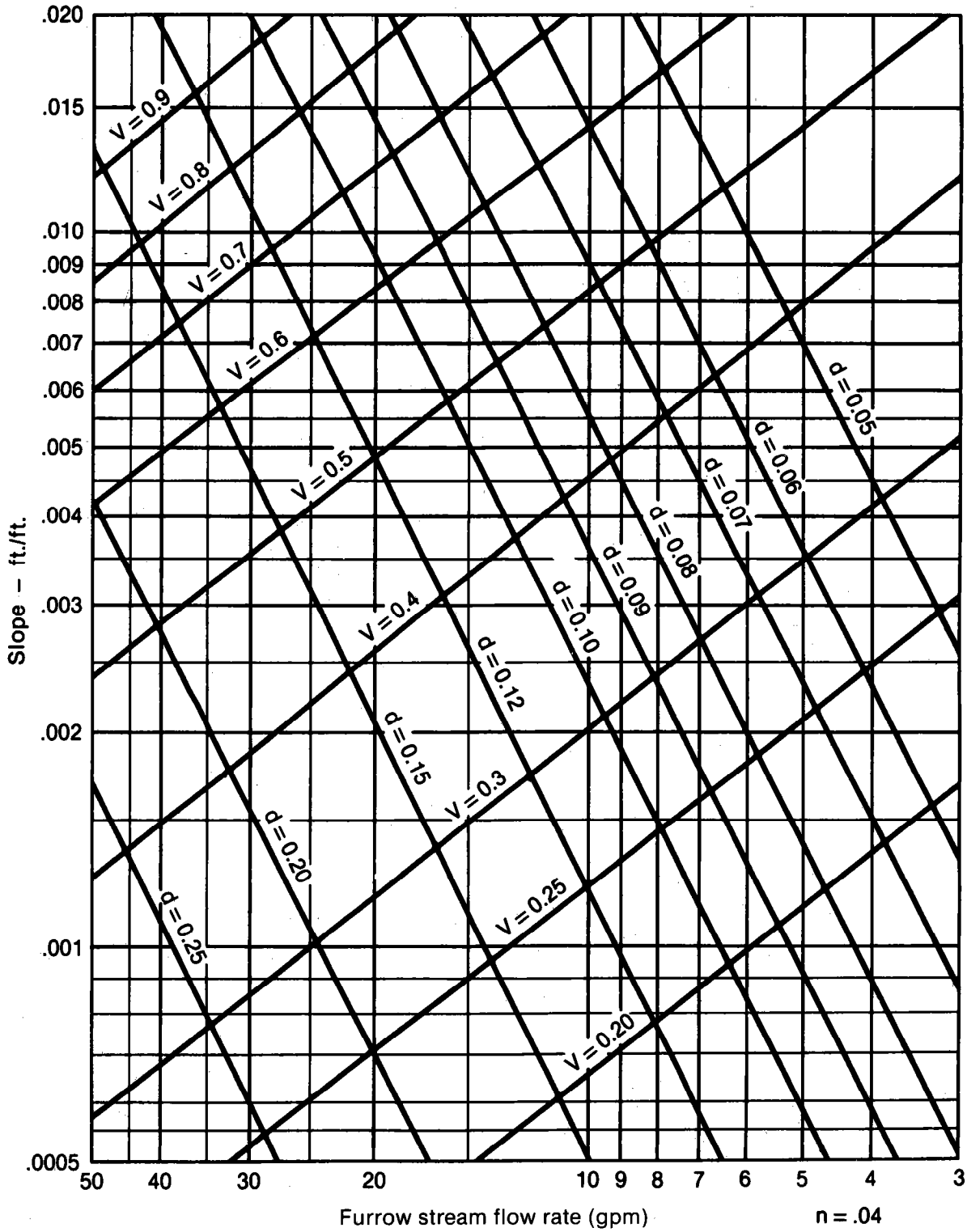
Gated pipe, siphon tubes, and spiles or ports in lined ditches are well suited for applying water by the cutback method. It may not be necessary to cut back the initial stream to get high irrigation efficiency on some soils. If at least three-fourths of the net intake is absorbed during the first one-fourth of the needed intake time, the use of cutback streams is questionable. An example is a fine-textured soil that cracks on drying.

Impoundment

The impoundment method requires that water be introduced rapidly so that the entire furrow length is wetted in a minimum time and the water impounded or held in place until the required application has entered the soil. This method does not require recovery or disposal of tailwater. It can be used for level furrows or where the fall in the total length of the furrow does not exceed the design depth of application. Impoundment can also be used on only the lower part of a graded furrow by impounding water that would otherwise be surface runoff.

Figure 5-13

Furrow Stream Velocity and Flow Depth



Continuous Inflow and Recovery

Many irrigators desire a water-application procedure by which they can obtain uniform, efficient irrigation by using a continuous inflow rate and avoid the added labor required in the cutback procedure. Irrigators often sacrifice both efficiency and uniformity of application merely for operating convenience or to minimize labor requirements. They do this by applying too small a furrow stream for longer than needed to obtain the desired intake rate. For the irrigator's convenience, this application time is usually in multiples of 12 hours. With the critical needs to use available water supplies with maximum efficiency and to conserve energy, this method of operation may become unacceptable. For efficient irrigation with a continuous inflow rate, it is usually necessary to provide for recovery of the irrigation tailwater and to apply furrow streams large enough to meet adequately the soil's intake requirements. The tailwater should be collected and reapplied to the furrows or corrugations or used on other irrigated fields. The design of tailwater-recovery pits is discussed in a later section.

Application Depth

The general irrigation practice has been to determine the root-zone depth of a mature crop, estimate the available water capacity of the soil to this depth, and design the system to apply 40 to 50 percent of this amount of water at each application. This practice does not always provide the best environment for plant growth. It is generally assumed that a crop will extract approximately 70 percent of its water requirement from the upper one-half of the zone in which the roots have developed. Most annual crops rated as deep-rooting crops have a root depth of 18 to 24 inches during most of the irrigation season. For maximum yields, water should be applied frequently enough to maintain a good water supply in the upper 12 to 18 inches of soil. This depth, of course, depends on the crop to be grown. To meet this requirement, a design net irrigation application of 2 to 4 inches is required for a corn or grain sorghum crop, depending on the water-holding capacity of the soil. If the soil is full of water at the start of the irrigation season, these frequent, relatively light water applications will provide readily available water for the crop throughout the growing season. In some areas of high rainfall, precipitation normally has filled the root zone of the soil to field capacity at the start of the growing season. In areas of low rainfall, it may be desirable to preirrigate and fill the soil to the mature root-zone depth of the crop to be grown. In either case, the growing crop starts out under field capacity water conditions.

The normal depth of application is defined as a full irrigation or the depth needed to bring the soil, within the water extraction depth of a mature crop, to field capacity after depletion to the management-allowed deficiency (MAD) level. MAD usually should not be greater than 50 percent of the total available-water-holding capacity of the soil. The total amount of soil water held available to plants in any soil is the sum of the available-water-holding capacity of all horizons occupied by plant roots.

Several other factors need to be considered when establishing the design application depth. It may be advantageous to increase or decrease the application depth to fit a practical application time schedule. A somewhat smaller application would result in only slightly fewer days between irrigations, and a larger application would result in a somewhat larger loss through deep percolation and a corresponding lower efficiency. Adjustments in design may also be needed if: (1) alternate furrows are to be irrigated, (2) smaller applications are desirable to leave storage capacity in the soil for rainfall, or (3) water supplies are limited to the extent that smaller-than-normal applications are made to ensure against crop failure rather than to produce maximum crop yields. The design depth must also be evaluated under conditions where smaller applications may be applied, such as early season irrigations.

In areas where irrigation water is in short supply and rainfall can normally be expected to supplement the irrigation water, it is permissible to allow the water level to drop below the recommended levels, except during the critical crop production stages, such as tasseling to denting stage for corn. Under these conditions, alternate furrow irrigation is frequently practiced, whereby only a percentage of the area between the furrows receives a complete irrigation. These factors must be considered in selecting the proper furrow design.

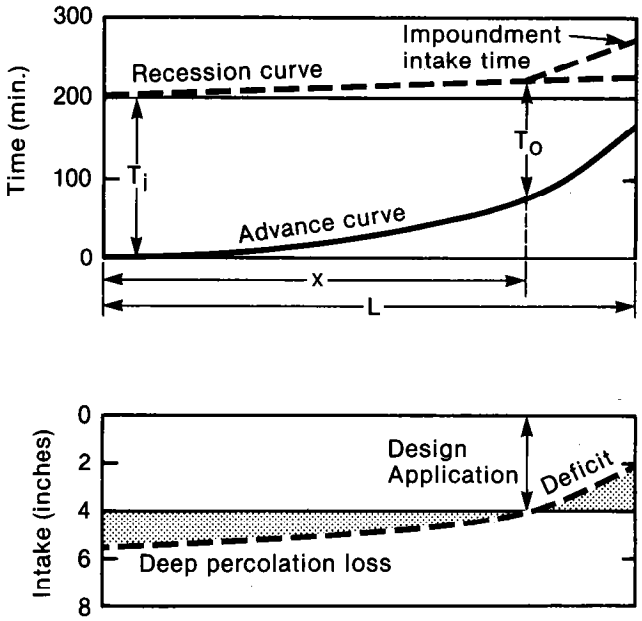
Assumptions

Some assumptions or approximations must be made in developing design equations and tables for

furrow and corrugation systems. These assumptions are valid enough that designs based on them result in irrigation systems that operate efficiently and uniformly, with only seasonal adjustments in stream size and application time. Design assumptions are made for the intake-time relationship, rate of advance, time for recession, opportunity time, retardance coefficient, and intake as related to furrow-wetted perimeter. (See fig. 5-14.)

Figure 5-14

Application Time, Advance and Recession Time vs. Intake Relationship



Intake-Time Relationship

Theoretically, intake uniformity along the entire length of a furrow would require that the intake time be equal at all points along the furrow. This is not possible with furrow or corrugation irrigation where water is applied at the upper end and progresses down the furrows with time. The length of time that water is in contact with segments of the system is, therefore, different at different points along the furrows or corrugations. For acceptable uniformity and adequacy of application, the minimum time that water is in contact with any point along the furrow length should not be less than that required for intake of the desired net application. Also, the maximum application time should be such that deep percolation losses are not excessive.

The time that water is in contact with a given segment of the furrow is defined as the opportunity time (T_o), or the amount of time that elapses after the furrow stream reaches the furrow stations until that water disappears from the surface at these points. This is the time increment between the advance and recession curves. These two curves are of prime importance in the design of a furrow or corrugation irrigation system because they describe the intake opportunity time for the various segments along the furrow length.

Advance Time

The rate of advance is influenced by the water inflow rate, the soil intake rate, and the furrow shape, grade, length, and surface roughness. The flow rate is largest at the upper end of the furrow and becomes successively smaller at each point downstream as water infiltrates. The result is a reduction in the rate of advance at successive points downstream. If the furrow length is such that the entire stream is absorbed by the soil, the advance stops. For efficient irrigation, advance must be rapid throughout the length.

Recession Time

The time for outflow of water to stop after inflow at the head of the furrow has ended is defined as recession time (T_r). This time is mostly affected by flow rate and furrow length, shape, and slope. The furrow surface generally becomes relatively smooth during the irrigation period so that retardance has progressively less influence on recession. Accumulation of crop residues in the furrows greatly affects the rate of advance, and, to a lesser degree, the rate of recession. In graded furrow or corrugation irrigation, the recession curve is relatively flat. If grades exceed approximately 0.25 percent, the recession time is so short that it has little effect on the soil intake. If the grade is 0.05 percent or less, impoundment of the stream can be used to increase the recession time and, in this manner, balance the advance-recession curve.

Because the recession time is relatively short compared with the needed intake time, it has little influence in graded furrow design. Recession time is considered when determining the opportunity time for a selected station. It is shown as zero in design equations for graded furrows, however, because a

period of time is required for the furrow stream to build to the design flow volume after the advance stream reaches the design station, and this required buildup time and the recession time, for practical purposes, cancel each other.

Opportunity Time

The design of a furrow system is based partly on opportunity time (T_o), the time that water is in contact with a given station in the furrow. For a constant inflow rate, the infiltration of water into the soil is less at successive points along a furrow length because of a reduction in both flow rate and opportunity time. A design based on the opportunity time needed at the upper end would result in inadequate intake for all successive stations down the furrow.

A furrow-system design based on the opportunity time needed for intake at the distal end of the furrow results in excessive intake at all stations upstream. Because the rate of advance decreases rapidly with increased length, systems can be designed to provide the opportunity time needed to apply the desired application at a point less than the entire length, for example, approximately 80 percent of the total length from the upper end. The best balance must be determined between excess application at the upper end and insufficient application in the section below the design point. For specific crops, this point must be selected after determining the effect of the application deficiency downstream of the design point.

Retardance Coefficient

The roughness or retardance in the furrow determines the velocity and depth of flow that result when a specified flow rate is applied in a furrow of a certain cross section and grade. This retardance is represented by the Manning "n" in the equation

$$Q=\left(\frac{666.96}{n}\right)\left(\frac{A^{5/3}\,S^{1/2}}{P^{2/3}}\right)$$

where

Q = flow in gpm

n = roughness coefficient

P = wetted perimeter of furrow in feet

S = furrow slope in feet per foot

A = cross-sectional area of water in the furrow in square feet

The Manning "n" varies with the furrow roughness and shape and the flow rate. Furrow roughness is readily altered by farm tillage equipment. Furrow and corrugation shapes also vary and, therefore, designs are based on the most common shapes. With the retardance condition and shape of the furrows standardized, the flow rate becomes the determining factor. The flow rate for most furrow streams is about 10 to 30 gpm and for most corrugation streams, 4 to 10 gpm. A study of furrow flows within this range indicates that designs based on retardance "n" value of 0.04 for furrows and 0.10 for corrugations result in design values most appropriate for these methods of water application.

Wetted Perimeter

The wetted perimeter of a furrow or corrugation at any point is the cross-sectional area that is in contact with the flowing stream. The rate of infiltration in a furrow or corrugation is a function of this area. This contact area decreases as the distance from the inflow end increases. Therefore, the design formulas must take into account this decrease in wetted area to determine the intake at a given point along a furrow.

Intake-Family Curves

A series of intake-family curves have been developed that relate cumulative depth of intake to opportunity time. Each type of soil has unique intake characteristics. Many soils, differ so little, however, that for practical purposes they can be grouped in one of a number of intake families. For design purposes, most soils, except those that crack by the time irrigation is needed, can be associated with one of these families. If the soil has a higher or lower intake rate at the time of a specific irrigation, the application rate and time can be adjusted accordingly by use of a higher or lower adjacent intake-rate curve. The intake curves developed for furrow or corrugation irrigation have the same general shape as curves developed for the border- and contour-ditch methods. The furrow curves on a specific site are not necessarily the same as the border curves but should generally be parallel. There is no simple guideline, such as soil texture, to govern the placement of a soil in a specific group. If field experience is inadequate to group the soils properly, field evaluations should be made. Such evaluations provide reliable data for furrow and corrugation designs on specific soils of an area.

The general formula describing the intake-family curves is:

$$F = aT_o^b + 0.275$$

where

F = cumulative intake in inches for time, t

a = intercept of cumulative intake at unit time

T_o = opportunity time in minutes

b = exponent of time in intake equation

The values for a and b are listed on figure 5–15 and in table 5–9.

Limitations

Furrow- and corrugation-design tables and charts allow a wide selection in length of run and grade and furrow streams. However, for efficient uniform water application, specific guidelines or limitations should be observed in selecting the design to be recommended. Limitations include permissible deep percolation losses, allowable amount of irrigation water runoff, and minimum application efficiency.

Deep Percolation

Water that percolates below the root zone of the crop not only is lost to the plants but frequently contributes to a buildup of the ground-water level, which may damage or destroy lower lying land where water returns to the surface and waterlogs the soil. In addition to the loss of water, deep percolation results in the loss of plant nutrients. An acre-inch of water that percolates below the root zone frequently carries with it as much as 4 to 5 pounds of nitrogen. It may also unnecessarily leach soluble minerals from the underlying strata.

Runoff

Water-use regulations in many states now prohibit an irrigator from allowing irrigation water to leave his land. Runoff water frequently contains colloidal material, minerals, and pesticides that are detrimental to adjoining landowners or to surface water. Runoff water can also be detrimental if ponded on neighboring farms or public or private property. It is extremely difficult to have efficient furrow or corrugation irrigation without tailwater. Provisions must be made for recovery or safe disposal of all runoff resulting from irrigation, regardless of the operating procedures used. Runoff from rainfall is not so easily regulated. However, the system design must include needed facilities for its safe disposal.

Design Efficiency

Design efficiency is defined as the ratio of the desired depth of irrigation to the gross depth of irrigation water applied. If the design depth of application is planned for a section other than the total length, such as 80 percent of the furrow or corrugation length, the design efficiency is expressed as DE_{80}. Optimum efficiency may not always be practical to obtain. Designs selected to fit the individual field requirements generally should have efficiency of no more than 10 percent below the optimum.

Equations

Design equations have been developed that describe the relationship between furrow length, inflow time, inflow rate, deep percolation, surface runoff, and field application efficiency for selected design values of application depth, soil intake family, and furrow slope and spacing.

Separate design equations and procedures are shown for each of the three types of furrow or corrugation irrigation:

1. Graded furrows or corrugations with open ends.
2. Cutback-inflow furrows with open ends.
3. Level-impoundment furrows.

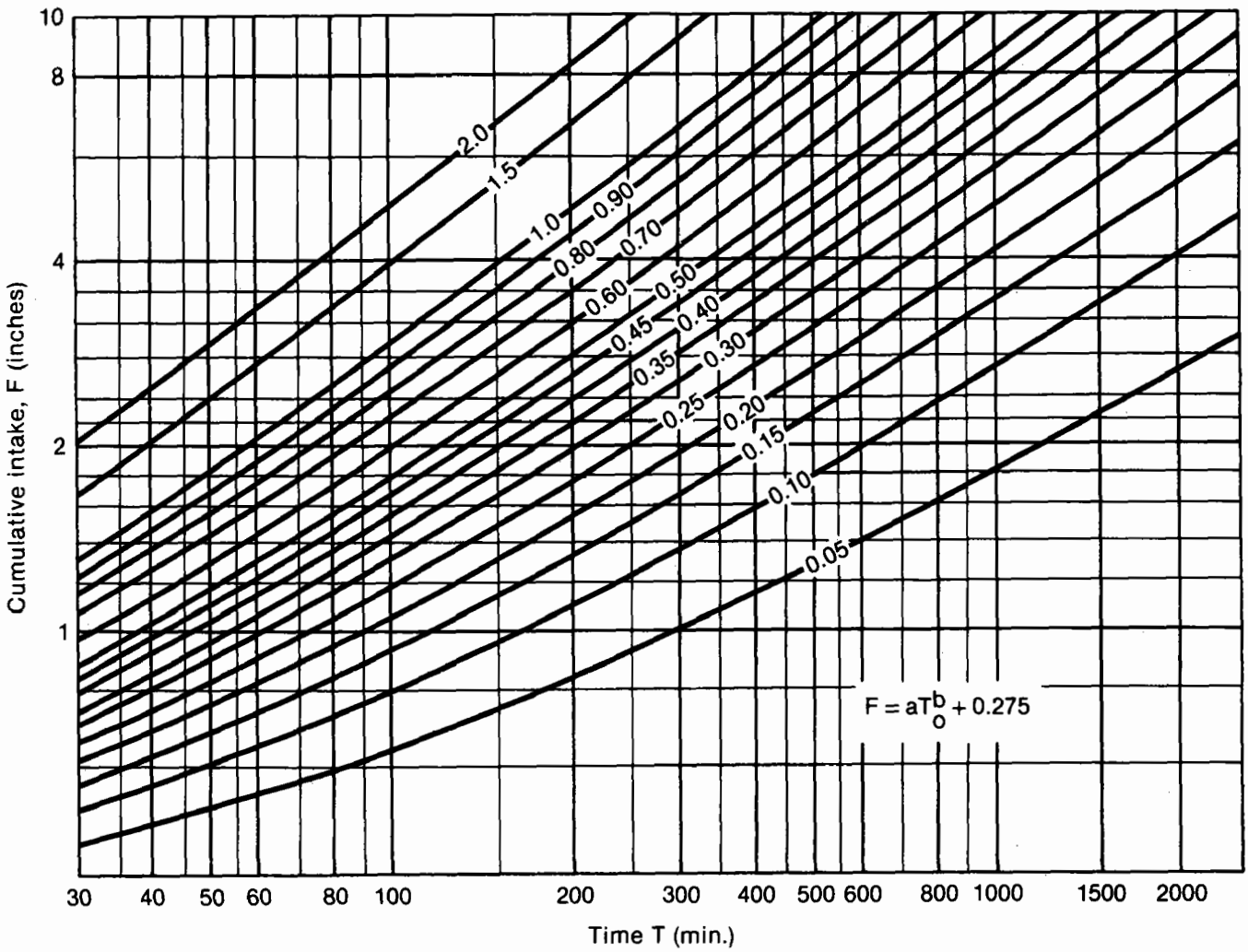
Graded Furrows

Equations for system design have been developed for the following items that must be determined in preparing a furrow or corrugation design: (1) wetted perimeter, (2) advance time or travel time, (3) opportunity time, (4) gross application depth, (5) intake depth at selected length, (6) average intake over the entire length of furrow, (7) surface runoff, (8) deep percolation, and (9) field application efficiency. All depths are expressed as equivalent depths over the furrow spacing.

Wetted perimeter.—The opportunity for water intake from a furrow is directly related to the cross section that is in contact with the water. The contact

Figure 5-15

Intake-family Curves



area per unit of length is the wetted perimeter and can be defined from the Manning formula as follows:

$$A = Bd + zd^2$$

$$P' = B + 2\sqrt{d^2 + (zd)^2}$$

$$Q = AV = A\frac{1.486}{n}\left(\frac{A}{P}\right)^{2/3} S^{1/2}$$

$$\frac{Qn}{S^{1/2}} = \frac{1.486\,A^{5/3}}{P^{2/3}}$$

A relationship between wetted perimeter and $Qn\,S^{-1/2}$ is derived using a minimum bottom width of 0.2 foot with 1:1 side slopes and a maximum bottom width of 0.5 foot with 2:1 slopes, and a number of cross-sectional shapes between these two extremes.

The resulting equation for wetted perimeter after units conversion is:

$$P' = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.0462$$

where

P' = wetted perimeter, ft

Q = furrow inflow, gpm

n = Manning roughness coefficient

S = furrow slope, ft/ft

Intake from a furrow occurs only over the part of the soil surface that is in contact with the furrow stream or the wetted perimeter of the furrow. However, intake is vertical and horizontal in contrast to flooding or sprinkler methods where intake is only vertical. To account for both vertical intake, which is influenced by gravitational forces, and horizontal intake, which is influenced by suction forces, the wetted perimeter is increased by an empirical constant of 0.700. This factor is an average value derived from studies that indicate that horizontal intake is a function of the 0.4 power of intake opportunity time.

The relationship for wetted perimeter, after adding the constant for horizontal intake, becomes:

$$P = 0.2686\ (Qn/S^{0.5})^{0.4247} + 0.7462 \qquad (5\text{-}1)$$

The value of P determined from equation 1 cannot exceed the furrow spacing W. Values of wetted perimeter plus constant are given in table 5-8 for selected inflow rates and furrow slopes.

Advance time.—The reduction of the stream as it travels down the furrow results in decreasing velocity and thus a continually decreasing rate of advance along the length of the furrow.

A regression analysis of velocity advance was made from several hundred furrow trials to relate effect of inflow rate, slope, length, and furrow-intake family. These studies resulted in a semilogarithmic equation for advance time in the form:

$$T_t = \frac{x}{c}\, e^{(dx/QS^{1/6})} \qquad (5\text{-}2)$$

where

T_t = advance time, minutes

x = furrow length to point x, feet

Q = inflow rate, gpm

S = furrow slope, ft/ft

c = advance coefficient varying with furrow-intake family

$c = (23.211 + 5.8653\ I_f)$

d = advance coefficient varying with furrow-intake family

$d = (4.4685 \times 10^{-4} + 1.5764 \times 10^{-3}\ I_f)$

I_f = furrow-intake family number

TABLE 5-8.—*Wetted perimeter plus constant (feet)* [1]

Furrows
n = 0.04

Q	S (ft/ft)								
(gpm)	0.0005	0.001	0.002	0.004	0.006	0.008	0.010	0.020	0.030
2	.....	.....	1.09	1.04	1.02	1.00	0.99	0.96	0.94
4	.....	.....	1.21	1.14	1.11	1.09	1.07	1.03	1.01
6	.....	.....	1.29	1.22	1.18	1.15	1.14	1.08	1.05
8	.....	.....	1.37	1.28	1.24	1.21	1.19	1.13	1.09
10	1.66	1.54	1.43	1.33	1.29	1.25	1.23	1.16	1.13
15	1.83	1.68	1.56	1.44	1.39	1.35	1.32	.....	.....
20	1.97	1.81	1.66	1.54	1.47	1.42	.....	.....	.....
25	2.10	1.91	1.75	1.61	1.54	.....	.....	.....	.....
30	2.20	2.00	1.83	1.68	.....	.....	.....	.....	.....
35	2.30	2.09	1.91	1.75	.....	.....	.....	.....	.....
40	2.39	2.17	1.97	1.81	.....	.....	.....	.....	.....
45	2.48	2.24	2.04	.....	.....	.....	.....	.....	.....
50	2.56	2.31	2.10	.....	.....	.....	.....	.....	.....

Corrugations
n = 0.10

Q	S (ft/ft)						
(gpm)	0.004	0.006	0.008	0.01	0.02	0.03	0.04
2	1.25	1.15	1.15	1.11	1.06	1.03	1.01
4	1.43	1.29	1.29	1.23	1.16	1.13	1.11
6	1.56	1.39	1.39	1.32	1.24	1.20	1.17
8	1.60	1.47	1.47	1.40	1.31	1.26	1.23
10	1.75	1.54	1.54	1.46	1.36	1.31	1.28

[1] Values of P cannot exceed furrow spacing W.

The maximum length of advance is reached at the point at which the volume of intake along the furrow length equals the volume of inflow. The advance time equation is not applicable to furrow slopes of less than 0.05 percent.

Intake family and advance coefficients are listed for various intake-family numbers in table 5-9. Figures 5-16(a) through 5-16(f) describe advance time in relation to furrow length for intake families ranging from $I_f = 0.05$ to $I_f = 2.0$. The curves are developed for an inflow rate of 1 gpm and a specific furrow slope. Curves are shown for slopes of 0.0005, 0.001, 0.005, 0.01, 0.02, and 0.03 ft/ft.

TABLE 5-9.—*Furrow-intake family and advance coefficients*

I_f	a	b	c	d
0.05	0.0210	0.6180	23.5040	5.2567×10^{-4}
.10	.0244	.6610	23.7975	6.0449×10^{-4}
.15	.0276	.6834	24.0908	6.8331×10^{-4}
.20	.0306	.6988	24.3841	7.6213×10^{-4}
.25	.0336	.7107	24.6773	8.4045×10^{-4}
.30	.0364	.7204	24.9706	9.1977×10^{-4}
.35	.0392	.7285	25.2639	9.9859×10^{-4}
.40	.0419	.7356	25.5511	1.0774×10^{-3}
.45	.0445	.7419	25.8504	1.1562×10^{-3}
.50	.0471	.7475	26.1436	1.2350×10^{-3}
.60	.0520	.7572	26.7302	1.3427×10^{-3}
.70	.0568	.7656	27.3167	1.5503×10^{-3}
.80	.0614	.7728	27.9032	1.7080×10^{-3}
.90	.0659	.7792	28.4898	1.8656×10^{-3}
1.00	.0703	.785	29.0763	2.0232×10^{-3}
1.50	.0899	.799	32.0090	2.8114×10^{-3}
2.00	.1084	.808	34.9416	3.5996×10^{-3}

The following example illustrates use of the figures for a slope of 0.005 ft/ft, furrow length of 900 feet, inflow rate of 10 gpm, and a furrow-intake family of 0.3.

$$\frac{\text{Furrow length}}{\text{Inflow rate}}=\frac{900}{10}=90$$

At the intersection of $\frac{L}{Q}=90$ and $I_f=0.3$, read the ratio $\frac{T_t}{Q}$ as 11.6. Advance time is then $11.6\times10\text{ gpm}=116$ minutes.

Recession time.—The amount of time it takes for water to disappear from the furrow after inflow stops is termed recession time. After inflow stops, water in the furrow is removed by the flow continuing down the furrow and/or by infiltration into the soil. The time of recession increases at successive points downstream.

Recession time for graded furrows with open ends is comparatively short and has little effect on the quantity of intake. The time required for the furrow stream to increase to a quantity used in the design after it reaches a specified station and the time of recession from that point tend to balance each other so that recession time can be omitted from the design criteria for graded furrows with open ends. Time of recession is significant for low graded or level furrows with blocked ends. Runoff is eliminated in these types of furrow systems and a different design procedure is required, which will be described separately.

Intake opportunity time.—Another factor influencing design is the intake opportunity time, the time water is available for infiltration at any point along the furrow. The opportunity time (T_o) also decreases at successive points downstream and depends on the inflow time, the advance time, and the recession time as shown by the following equation:

$$T_o=T_i-T_t+T_r$$

Inflow time (T_i) is a constant for a specific irrigation. Advance time (T_t) increases at successive points downstream. Recession time (T_r) is assumed to be zero for graded open-end furrows. This assumption results in an equation for opportunity time at any given point (x) along the furrow as follows:

$$T_o=T_i-T_t$$

Substituting equation 2 for T_t yields:

$$T_o=T_i-\frac{x}{c}e^{(dx/QS^{1/2})} \qquad (5\text{-}3)$$

where

T_o = intake opportunity time in minutes at any point, a distance of x from the inlet. The subscript n is used rather than o to describe the net opportunity time required for a cumulative intake F_n.

T_i = inflow time in minutes.

It is also necessary to determine the average intake opportunity time for the entire furrow length to determine the total amount of applied water that has infiltrated. The average opportunity time, assuming recession time is 0, is equal to the inflow time (T_i) less the average advance time. The average advance time is determined by integration of advance equation 2 between the limits of 0 and L and dividing by the length L.

$$T_{(0\text{-}L)}=\left[T_i-\frac{1}{cL}\int_0^L L\ e^{(dL/QS^{1/2})}\right]$$

Integration by parts yields the following equation for average opportunity time:

Figure 5-16(a)

Advance Time vs. Length (S = 0.0005 ft./ft.)

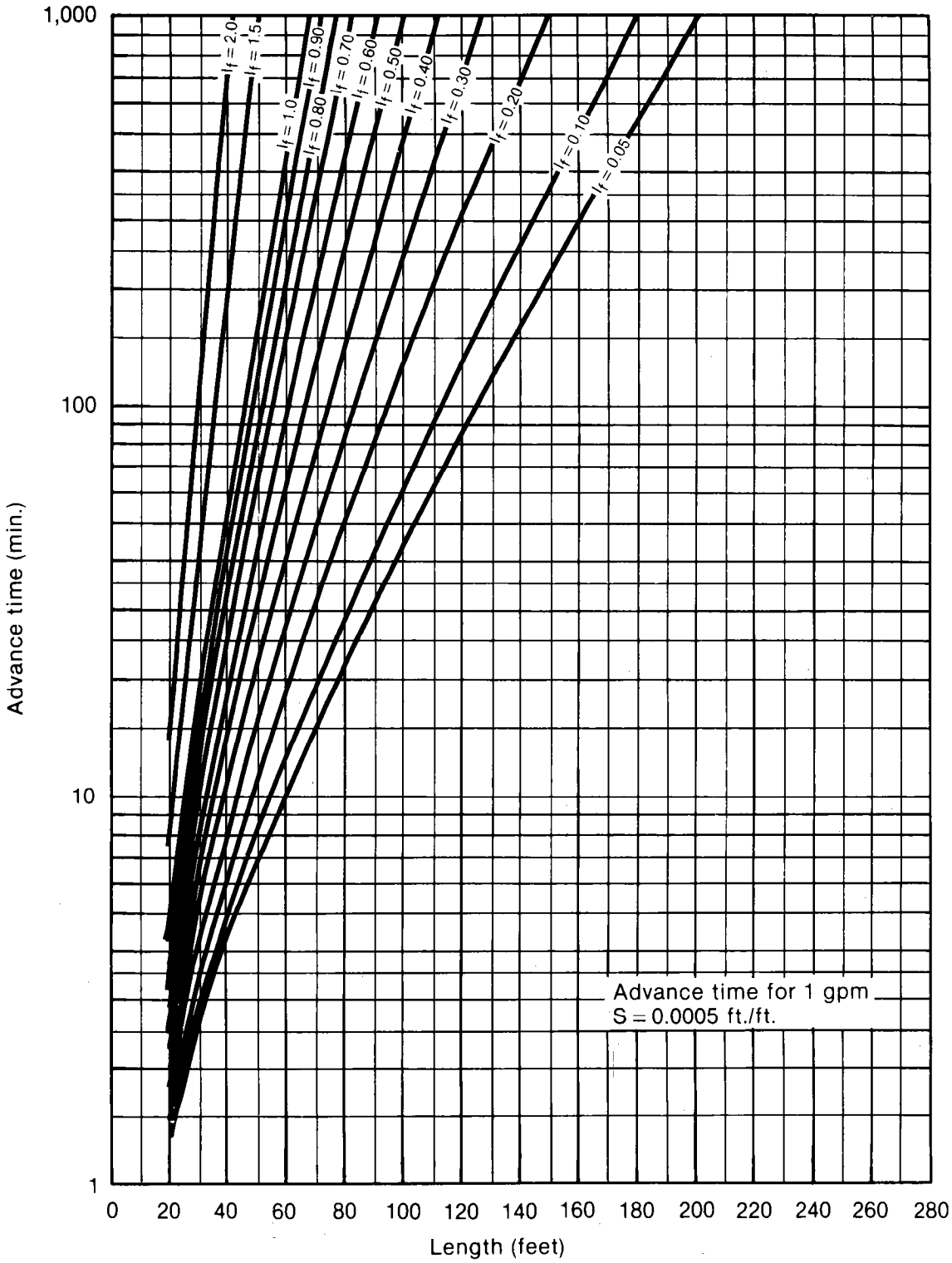


Figure 5-16(b)

Advance Time vs. Length (S = 0.001 ft./ft.)

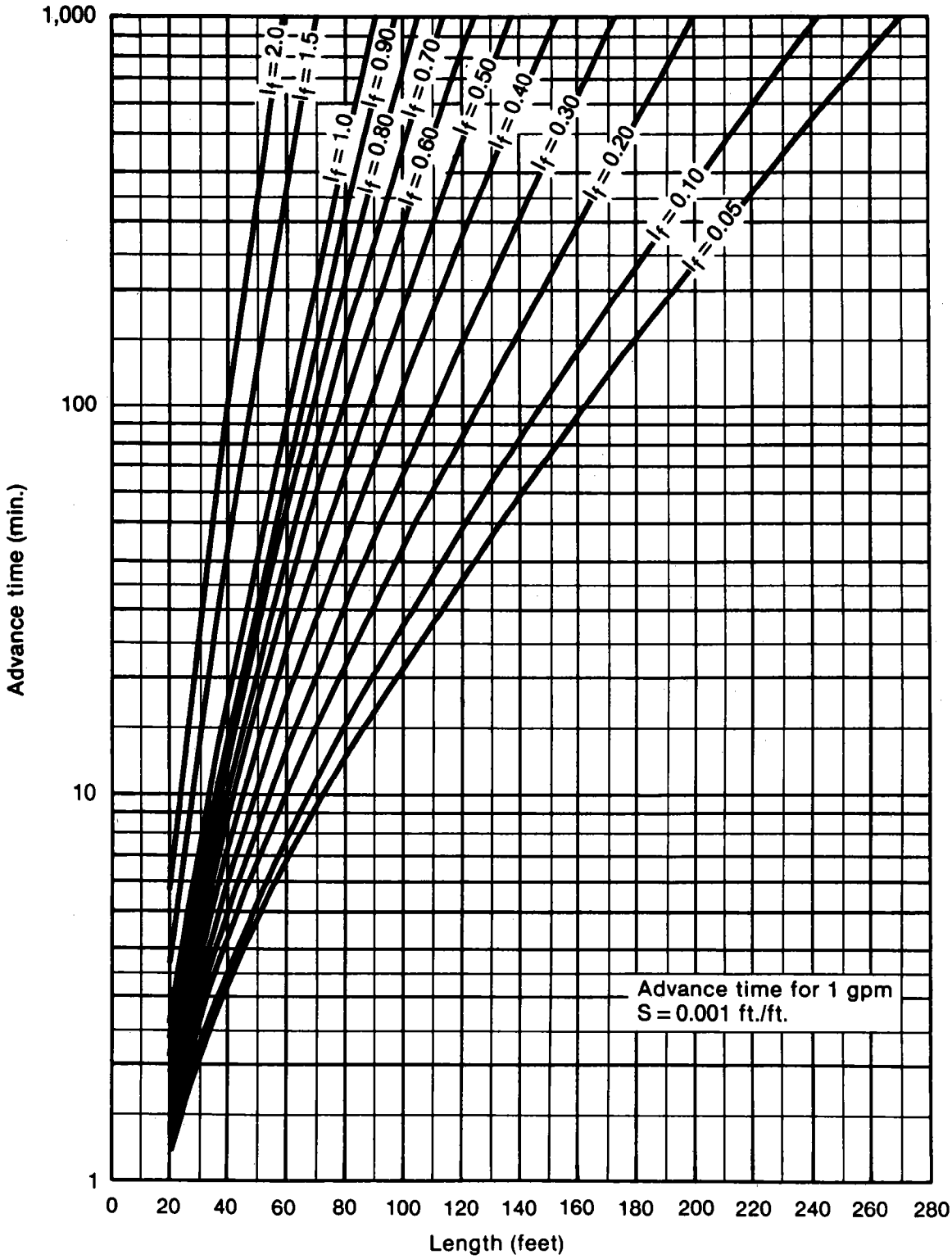


Figure 5-16(c)

Advance Time vs. Length (S = 0.005 ft./ft.)

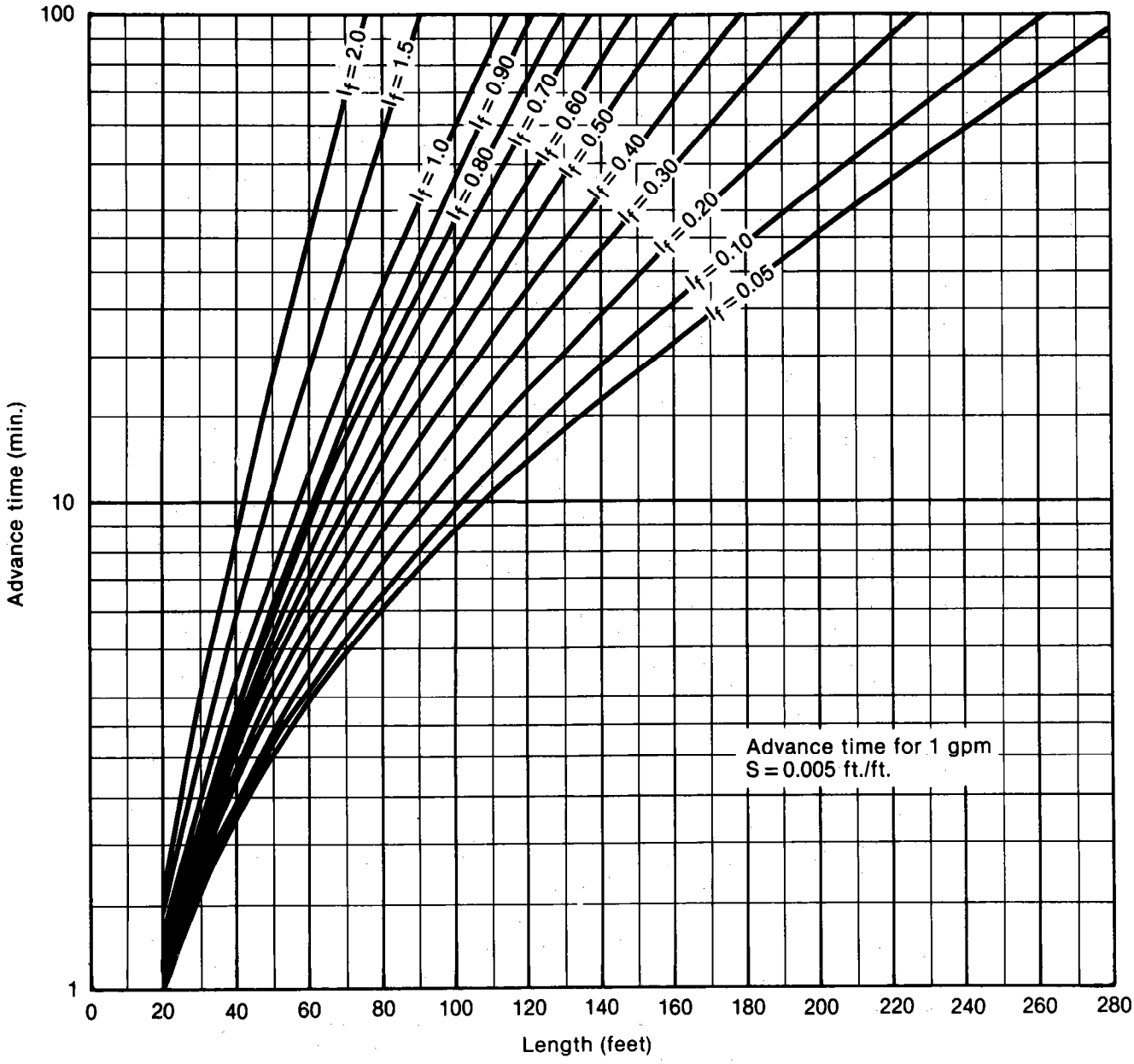


Figure 5-16(d)

Advance Time vs. Length (S = 0.01 ft./ft.)

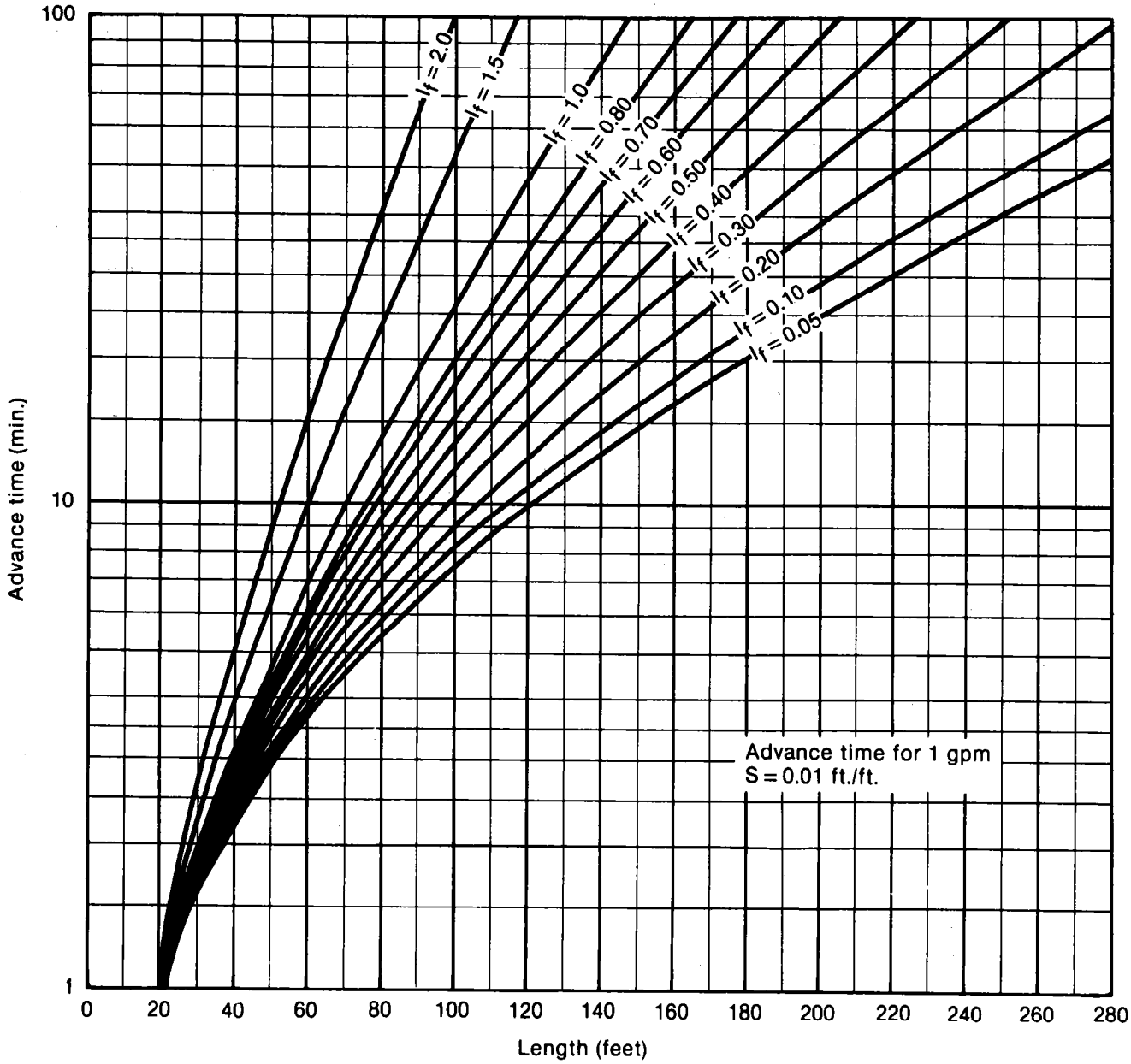


Figure 5-16(e)

Advance Time vs. Length (S = 0.02 ft./ft.)

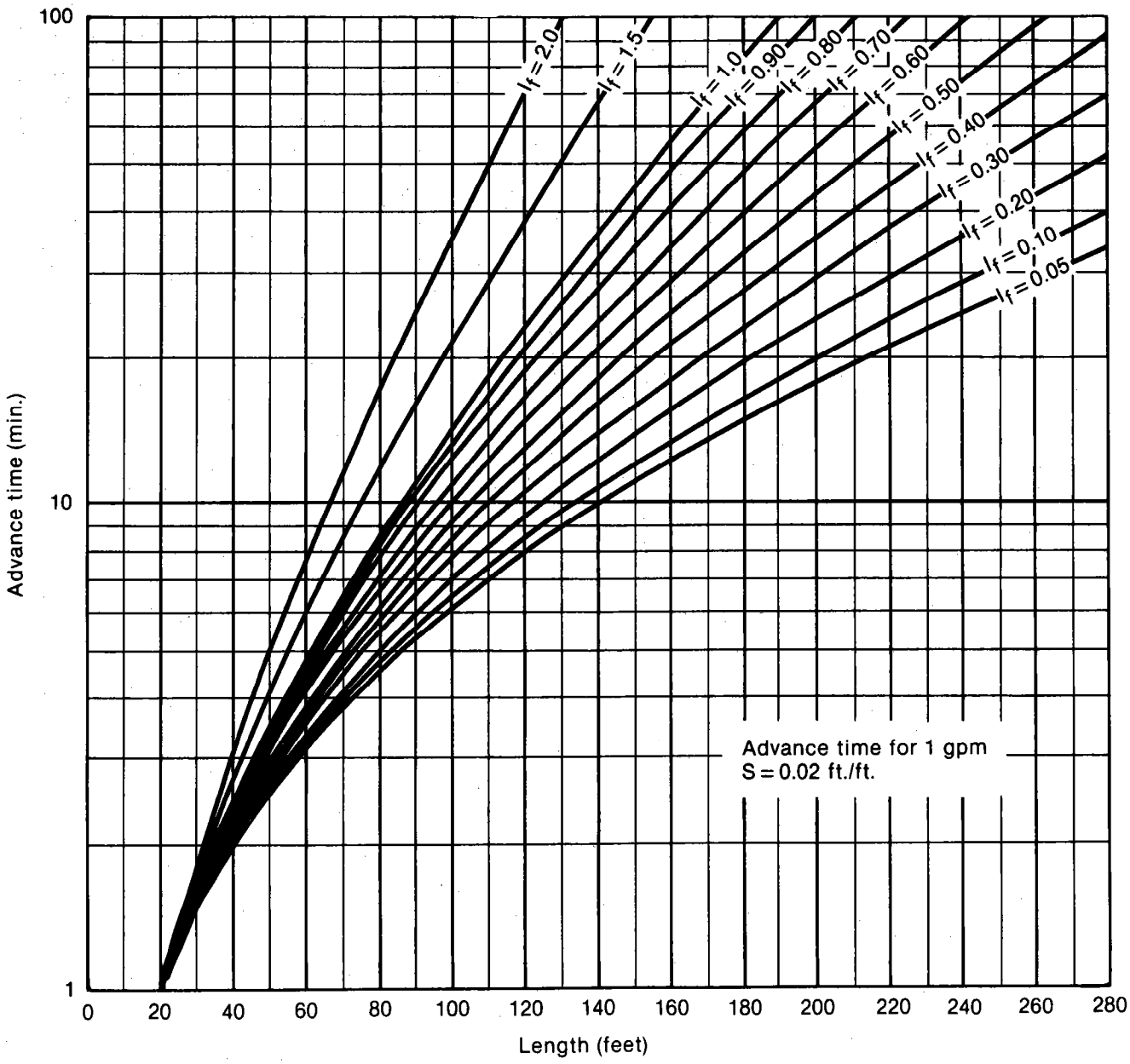
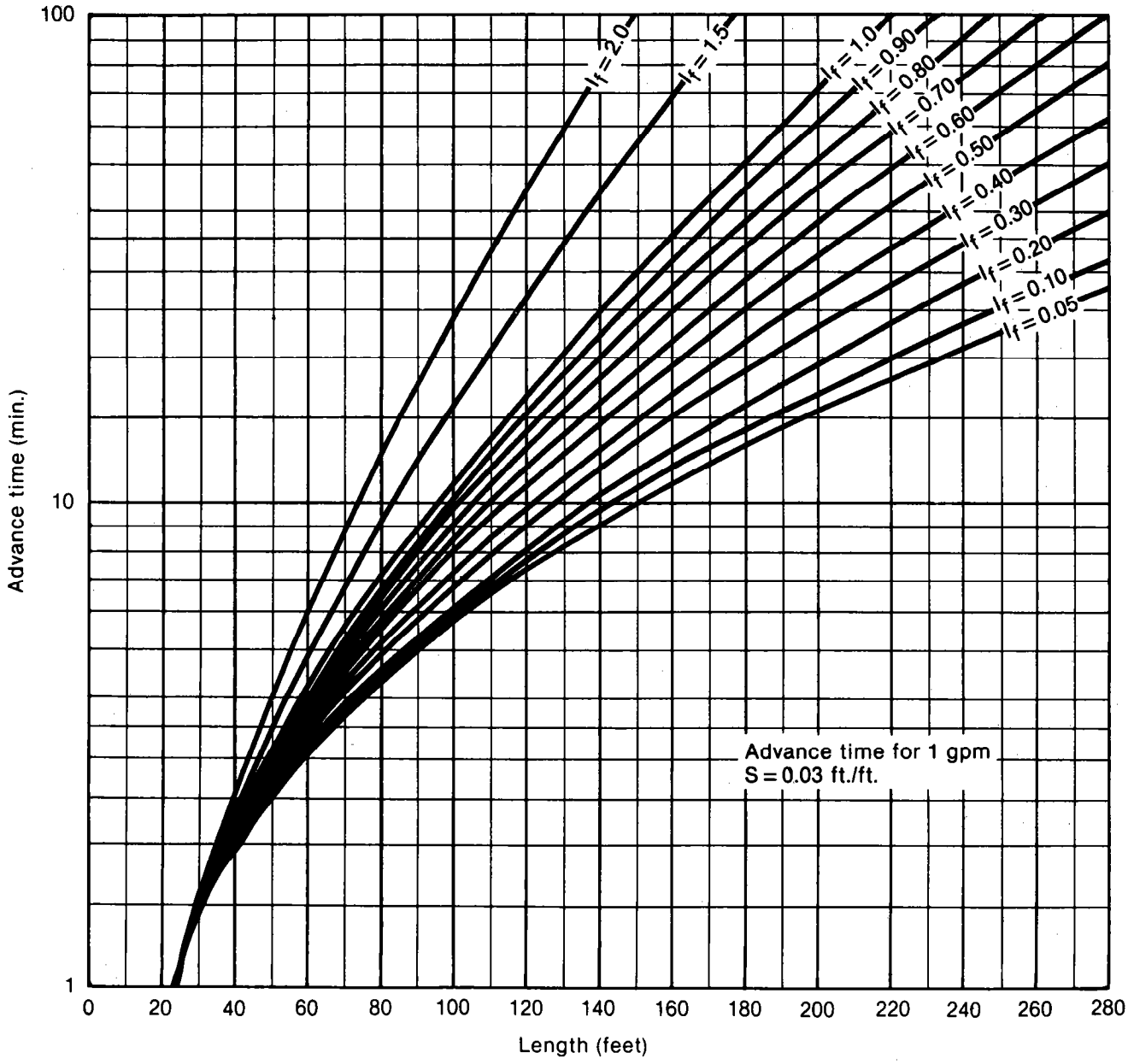


Figure 5-16(f)

Advance Time vs. Length (S = 0.03 ft./ft.)



$$T_{(0-L)} = T_i - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2} \left(\frac{dL}{QS^{1/2}} - 1 \right) e^{(dL/QS^{1/2})} + 1 \right] \quad (5\text{-}4)$$

where $T_{(0-L)}$ is the average opportunity time for the furrow length (L) in minutes.

The same equation can be used to determine the average opportunity time to point x, ($T_{(0-x)}$) along the furrow length by substituting the distance to point x for L in equation 4.

Gross application depth.—The gross application depth must be known to determine the amount of surface runoff and the application efficiency that can be expected with the selected design. The gross application depth can be calculated by use of the equation:

$$F_g = \frac{1.6041\ Q\ T_i}{WL} \quad (5\text{-}5)$$

where

F_g=gross depth applied, in

Q=inflow rate, gpm

T_i=application time, min

W=furrow spacing, ft

L=furrow length, ft

Intake depth.—The point intake at which the entire surface is covered by the irrigation stream is expressed by the intake equation in the formula:

$$F = (a\ T^b + 0.275)$$

where F is the point cumulative intake in inches; a and b are coefficients for each intake family as listed in table 5-9. T is the intake opportunity time at the intake point. Intake from a furrow occurs only over the portion of the soil surface that is in contact with the furrow stream or the wetted perimeter of the furrow. The wetted perimeter is adjusted by the addition of a constant (0.7) to account for both vertical and horizontal intake, as previously discussed.

The point intake equation for furrows is:

$$F = (a\ T^b + 0.275)\ (P)$$

Intake depth is normally expressed as the depth over the entire furrow width or area. The equivalent intake depth for furrows then becomes x at any point along the furrow length:

$$F_x = (a\ T_{ox}{}^b + 0.275)\ \frac{P}{W} \quad (5\text{-}6)$$

where

F_x=cumulative intake at any point x along the furrow in inches

T_{ox}=opportunity time at point x along the furrow in minutes

a & b=intake-family coefficients as given in table 5-9

P=wetted perimeter, in feet, determined from equation 1. The maximum value cannot exceed furrow spacing W.

W=furrow spacing in feet

Equation 6 can be used to determine the cumulative intake at any point x along the furrow. The designer may, for example, select a point x equal to 80 percent of the furrow length at which to apply the design application depth. Normally, furrow designs provide for application of the design depth at the end of the furrow and the subscripts of cumulative intake F and opportunity time T are changed to F_n and T_n, respectively.

Equation 6 then becomes:

$$F_n = (a(T_n)^b + 0.275)\ P/W \quad (5\text{-}7)$$

where F_n is the design depth in inches and T_n is the required opportunity time for the design depth.

The average cumulative intake for the entire furrow length can be determined using equation 7 by substituting the average opportunity time $T_{(0-L)}$ computed by using equation 4 for the opportunity time (T_n) at length L.

$$F_{(0-L)} = \left[a(T_{(0-L)})^b + 0.275 \right] P/W \quad (5\text{-}8)$$

The average cumulative intake ($F_{(0-x)}$) for a length less than L can also be determined by substituting the average opportunity time ($T_{(0-x)}$) in equation 8 for $T_{(0-L)}$.

Surface runoff.—Outflow from the end of a graded furrow is necessary to provide opportunity time for intake at the lower end of a furrow, unless the ends are blocked and the water is ponded in the furrow. Properly designed furrow systems must provide for recovery and reuse or safe disposal of the surface runoff. The expected average depth of runoff can be estimated by use of the equation:

$$RO = F_g - F_{(0-L)} \tag{5-9}$$

where RO = average surface runoff depth in inches.

The surface runoff can be expressed in volume units by the equation:

$$v_{RO} = \frac{RO\,(W)\,(L)}{12\,(43{,}560)} \tag{5-10}$$

where

v_{RO} = volume of runoff, acre-ft

RO = surface runoff, in.

W = furrow spacing, ft

L = furrow length, ft

Deep percolation.—Deep percolation is the average depth of irrigation water that infiltrates the soil in excess of the design application depth. Deep percolation is determined from the equation:

$$DP = F_g - RO - F_n \tag{5-11}$$

where DP = average deep percolation over the furrow length in inches. The equation can also be expressed as:

$$DP = F_{(0-L)} - F_n$$

When the design application, at the option of the designer, is to be applied at a point x that is less than the furrow length L, the equation for deep percolation expressed as equivalent depth over the entire length becomes:

$$DP = (F_{(0-x)} - F_n)\frac{x}{L} \tag{5-12}$$

Application efficiency.—The application efficiency is defined as the percentage of the applied irrigation water that is stored in the soil at design application depth. Efficiency as a decimal is expressed as the inflow volume less the runoff and deep percolation volumes, divided by the inflow volume.

The equation for efficiency if the design application is applied at furrow length L is:

$$AE = 100\,\frac{F_n}{F_g} \tag{5-13}$$

where AE is application efficiency in percent.

The equation for efficiency where the design application is applied at a point x that is less than the furrow length L becomes:

$$AE = 100\,\frac{(F_{(0-x)} - DP)}{F_g} \tag{5-14}$$

where

AE = application efficiency, percent

DP = deep percolation, inches, as computed in equation 12

Summary of Graded Furrow Equations

Wetted perimeter plus constant

(5-1) $$P = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.7462$$

Advance time

(5-2) $$T_t = \frac{x}{c}\,e^{(dx/QS^{1/2})}$$

Opportunity time

(5-3) $$T_o = T_i - \frac{x}{c}\,e^{(dx/QS^{1/2})}$$

Average opportunity time

(5-4) $$T_{(0-L)} = T_i - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]$$

Gross application depth

(5-5) $$F_g = \frac{1.6041\,Q\,T_i}{WL}$$

Cumulative intake at a point x

(5-6) $$F_x=(a\,T_{ox}{}^b+0.275)\frac{P}{W}$$

Cumulative intake at a design point

(5-7) $$F_n=(aT_n{}^b+0.275)\,P/W$$

Average cumulative intake for furrow length L

(5-8) $$F_{(0-L)}=\left[a\,(T_{(0-L)})^b+0.275\right]P/W$$

Runoff depth

(5-9) $$RO=F_g-F_{(0-L)}$$

Runoff volume

(5-10) $$v_{RO}=\frac{RO\,(W)\,(L)}{12\,(43{,}560)}$$

Deep percolation and application efficiency at length L

(5-11) $$DP=F_g-RO-F_n$$

(5-13) $$AE=100\,\frac{F_n}{F_g}$$

Deep percolation and application efficiency at length less than L

(5-12) $$DP=(F_{(0-x)}-F_n)\,\frac{x}{L}$$

(5-14) $$AE=100\,\frac{(F_{(0-x)}-DP)}{F_g}$$

Design Examples of Graded Furrows

Information available:

Type: Graded

Intake family: $I_f=0.3$

Design application depth: $F_n=3.0$ in

Length: $L=900$ ft

Slope: $S=0.004$ ft/ft

Spacing: $W=2.5$ ft

Roughness coefficient: $n=0.04$

Design assumptions:

(1) The water will spread laterally across the 2.5-ft furrow spacing.

(2) The design application is to be applied at the end of the 900-ft furrow.

Procedure:

(1) Assume the inflow rate Q is 10 gpm.

(2) Find intake and advance coefficients for the 0.3 intake family from table 5-9:

$$a=0.0364\quad b=0.7204\quad c=24.9706\quad d=9.1977\times10^{-4}$$

(3) Compute the advance time for the 900-ft furrow, using equation 2.

$$T_t=\frac{900}{24.9706}\,e\left(\frac{(9.1977\times10^{-4})\,(900)}{10\sqrt{0.004}}\right)$$

$$T_t=133\text{ min}$$

(4) Calculate the wetted perimeter plus constant using equation 1.

$$P=0.2686\left(\frac{Qn}{S^{0.5}}\right)^{0.4247}+0.7462$$

$$P=0.2686\left(\frac{(10\times0.04)}{\sqrt{0.004}}\right)^{0.4247}+0.7462=1.33\text{ ft}$$

or from table 5-8, find for $Q=10$ gpm
$P=1.33$ ft

(5) Calculate net opportunity time (T_n) required for design application (F_n) of 3.0 inches using equation 7.

$$F_n=(0.0364\,T_n{}^{0.7204}+0.275)\,\frac{P}{W}$$

Solving for T_n:

$$T_n=\left[\frac{\left((F_n\times\frac{W}{P})-0.275\right)}{0.0364}\right]^{1/0.7204}=1023\text{ min}$$

(6) Calculate the application time T_i:

$$T_i=T_t+T_n=133+1023=1{,}156\text{ min}$$

(7) Calculate the gross application:

$$F_g = \frac{1.6041\ Q\ T_i}{WL} = \frac{1.6041\ (10)\ (1{,}156)}{2.5 \times 900} = 8.2 \text{ in}$$

(8) Calculate the average opportunity time for the 900-ft furrow, $T_{(0-L)}$:

$$T_{(0-L)} = T_i -$$

$$\left[\frac{1}{cL\,(d/QS^{1/2})^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right) e^{(dL/QS^{1/2})} + 1\right]\right]$$

$$T_{(0-L)} = 1{,}156.7 - 45.1 = 1{,}111.6 \text{ min}$$

(9) Calculate average intake for the entire furrow length.

$$F_{(0-L)} = (aT_{(0-L)}{}^b + 0.275)\ P/W$$

$$F_{(0-L)} = (0.0364\ (1111.6)^{0.7204} + 0.275)\frac{1.33}{2.50} = 3.2 \text{ in}$$

(10) Calculate the deep percolation.

$$DP = F_{(0-L)} - F_n = 3.2 - 3.0 = 0.2 \text{ in}$$

(11) Calculate the surface runoff.

$$RO = F_g - F_{(0-L)} = 8.2 - 3.2 = 5 \text{ in}$$

(12) Calculate the application efficiency.

$$AE = 100\frac{F_n}{F_g} = \frac{100\ (3.0)}{8.2} = 37\%$$

(13) Summary of the results:

$I_f = 0.3$

$W = 2.5$ ft

$S = 0.004$ ft/ft

$F_n = 3.0$ in

$Q = 10$ gpm

$L = 900$ ft

$T_i = 1{,}156$ min

$RO = 5$ in

$DP = 0.2$ in

$AE = 37\%$

(14) Assume different inflow rates and repeat steps 1–12 until either an acceptable inflow time or application efficiency, or both, is obtained.

Procedure for Using Design Charts

A series of design charts similar to figures 5–17 and 5–18 can be prepared to simplify the design procedure for graded furrows and eliminate the use of solutions by equations. Each chart is for a specific intake family, furrow slope, design depth of application, furrow spacing, and Manning roughness coefficient. Each chart has four sets of inflow-rate curves describing the relationship of furrow length to: (1) inflow time, (2) deep percolation, (3) runoff, and (4) application efficiency. Solutions can be obtained from charts for a known or assumed value of either inflow rate, deep percolation, runoff, or efficiency paired with a known or assumed value of either inflow rate or furrow length. For example, for an assumed efficiency and inflow rate, the furrow length, runoff, deep percolation, and inflow time can be determined to provide the most practical farm operating schedule.

Charts can be converted to furrow spacings other than 30 inches by the following procedure:

1. Divide net application F_n by the ratio of 2.5 ft divided by the desired spacing in feet, which gives an adjusted net application.
2. Using the adjusted net application, select a chart that has an F_n value nearest the adjusted value.
3. From the selected chart read inflow time T_i, runoff RO, and efficiency AE.
4. Determine the gross depth of application F_g by multiplying the net application F_n from the selected chart by 100 and dividing by efficiency AE.
5. Multiply gross application F_g, design application F_n, and runoff RO by the ratio found in step 1 above to get adjusted gross application ($F_{g\ adj}$), adjusted design application ($F_{n\ adj}$) and adjusted runoff (RO_{adj}) for the desired furrow spacing.
6. Obtain adjusted deep percolation (DP_{adj}) by subtracting the sum of the adjusted design application ($F_{n\ adj}$) and the adjusted runoff (RO_{adj}) from the adjusted gross application ($F_{g\ adj}$).
7. No adjustment is required for the inflow time T_i, inflow rate Q, and efficiency AE. If a cutback method is to be used, further calculations are necessary.

Example

The following example illustrates the use of the design charts for a specific graded furrow irrigation

Figure 5-17

Graded Furrow Design Chart

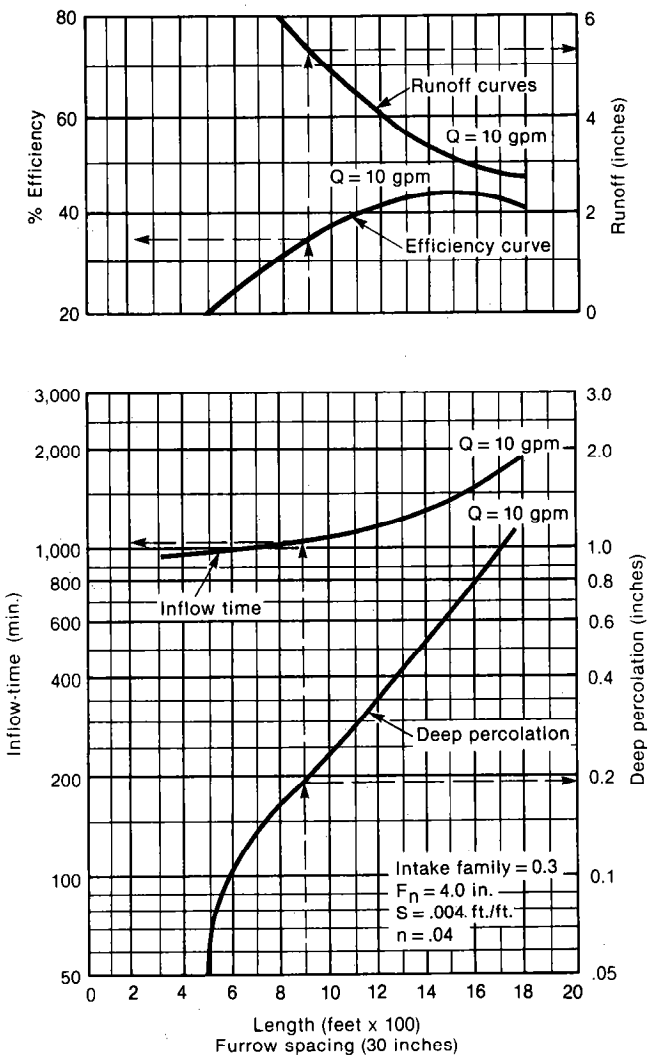
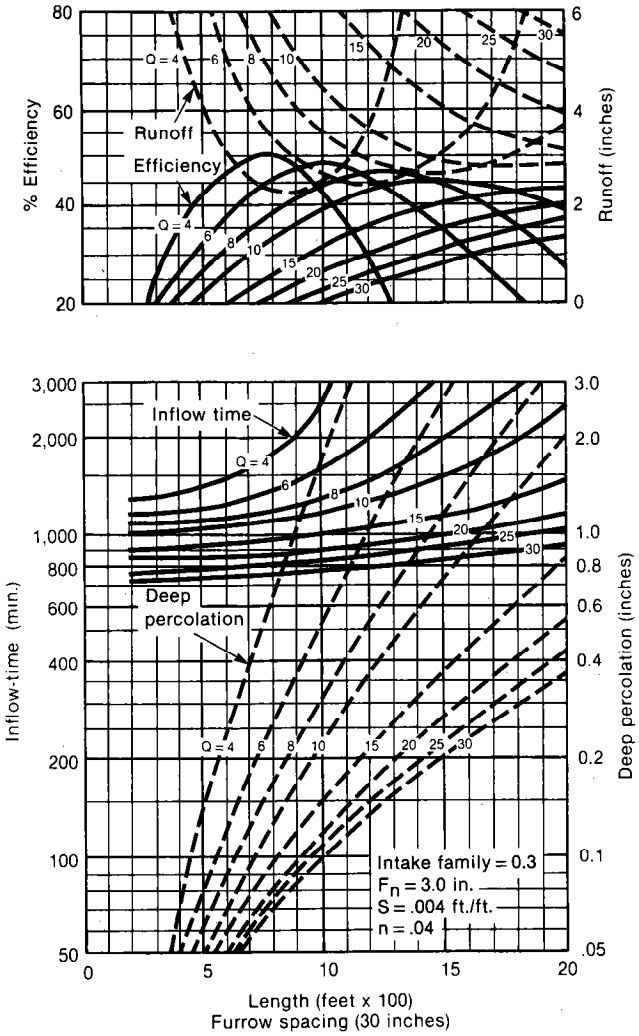


Figure 5-18

Graded Furrow Design Chart



system. The same information and assumptions are used as in the example illustrating solution by equations:

Intake family (I_f)=0.3

Design application depth (F_n)=3.0 in

Length (L)=900 ft

Slope (S)=0.004 ft/ft

Spacing (W)=2.5 ft

Roughness coefficient (n)=0.04

By using the chart in figure 5–18 and a furrow length of 900 feet, the following solutions are possible:

(1) Assume inflow time T_i is 18 hours or 1,080 minutes:

At the intersection of 1,080 minutes inflow time and 900 ft length on the various curves, the inflow rate is approximately 12 gpm, deep percolation is approximately 0.15 inch, efficiency is 33 percent, and runoff is 6 inches.

Using the same procedure, find solutions for the following:

(2) Assume efficiency is 49 percent.

AE=49%

L=900 ft

Find:

Q=5.0 gpm

RO=2.5 in

T_i=1,700 min=28.3 hr

DP=0.60 in

(3) Assume inflow rate is 10 gpm

Q=10 gpm

L=900 ft

Find:

T_i=1,150 min=19.2 hr

DP=0.2 in

RO=5.0 in

AE=37%

(4) Assume the furrow spacing in example 3 is 3.33 ft rather than 2.5 ft for which the chart was prepared. The following computations are necessary:

(a) Ratio=2.5 ft÷W=2.5 ft÷3.33 ft=0.750

Adjusted net application=3 in÷0.75=4.0 in

(b) Select chart, figure 5-17

(c) T_i=1,050 min=17.5 hr

RO=5.4 in

AE=35%

(d) F_g=(4.0 in×100)÷35%=11.4 in

(e) $F_{g\ adj}$=11.4 in×0.75=8.6 in

$F_{n\ adj}$=4.0 in×0.75=3 in

RO_{adj}=5.4 in×0.75=4 in

(f) DP_{adj}=8.6 in−(3 in+4 in)=1.6 in

Cutback-Inflow Method

The volume of surface runoff resulting from irrigations using a constant inflow rate can be reduced, and the application efficiency thereby significantly improved, by reducing the inflow rate for part of the application time. Such a cutback procedure increases the labor requirements because an adjustment to reduce the flow to the furrows must be made during the irrigation. Also, unless the supply flow is reduced at the source, the remaining supply flow must be either applied to other field areas or stored. If surface runoff from constant inflow graded furrows can be reused, the cutback method may not be desirable or feasible from a labor standpoint.

The assumption is made that in using the cutback-inflow method the initial flow rate will be reduced to one-half when it has advanced to the end of the open-end furrow. The time of cutback is then equal to the advance time as described by equation 2, after substituting length L for distance x:

$$T_t=\frac{L}{c}\,e^{(dL/QS^{1/2})}$$

The time required for intake of the design application F_{nc} at the end of the furrow is from equation 7:

$$T_{nc}=\left[\left(\frac{F_{nc}W}{P_1}-0.275\right)\frac{1}{a}\right]^{1/b} \qquad (5\text{-}15)$$

where P_1 is the wetted perimeter for the cutback-inflow rate Q/2 or:

$$P_1=0.2686\left(\frac{Qn}{2S^{0.5}}\right)^{0.4247}+0.7462$$

The total inflow time for the cutback method is then the sum of the opportunity time required at the end of the furrow T_{nc} and the advance time T_t or

$$T_{ic}=T_{nc}+T_t \qquad (5\text{-}16)$$

The average advance time, $T_{t_{ave}}$ is:

$$T_{t_{ave}}=\left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}}-1\right)e^{(dL/QS^{1/2})}+1\right]\right] \qquad (5\text{-}17)$$

The average opportunity time for intake during the time for the initial inflow rate to advance to the end of the furrow is described by the second term in equation 4, subtracted from travel time to furrow length, L or:

$$T_{o_{adv}}=T_t-T_{t_{ave}} \qquad (5\text{-}17a)$$

The average intake during the advance period then becomes, from equation 8:

$$F_{adv}=[a\,(T_{o_{adv}})^b+0.275]\,\frac{P}{W}$$

The average intake under cutback conditions is the sum of intake during the advance period and the intake during the remainder of the inflow time during which the inflow rate is reduced to one-half the initial inflow, or:

$$F_{(0\text{-}L)c}=[a\,(T_{ic}-T_{t_{ave}})^b+0.275]\,\frac{P_1}{W}+\left[(a\,T_{o_{adv}}{}^b+0.275)\,\frac{P}{W}-(a\,T_{o_{adv}}{}^b+0.275)\frac{P_1}{W}\right]$$

which becomes:

$$F_{(0\text{-}L)c}=[a\,(T_{ic}-T_{t_{ave}})^b+0.275]\,\frac{P_1}{W}+\left[\frac{(a\,(T_{o_{adv}})^b+0.275)\,(P-P_1)}{W}\right] \quad (5\text{-}18)$$

The gross application under cutback conditions becomes:

$$F_{gc}=\frac{1.6041}{WL}\,(Q\,T_t+\frac{Q}{2}\,T_{nc}) \quad (5\text{-}19)$$

Runoff, deep percolation, and efficiency under cutback conditions are:

$$RO_c=F_{gc}-F_{(0\text{-}L)c} \quad (5\text{-}20)$$

$$DP_c=F_{(0\text{-}L)c}-F_{nc} \quad (5\text{-}21)$$

$$AE_c=100\,\frac{F_{nc}}{F_{gc}} \quad (5\text{-}22)$$

Design tables or charts for the cutback-inflow method can be prepared for specific intake families and net application depths for a range of slopes, lengths, and flow rates to facilitate use of the design procedure.

Summary of Cutback-Inflow Equations

(5-2) $$T_t=\frac{L}{c}\,e^{(dL/QS^{1/2})}$$

(5-1) $$P=0.2686\left(\frac{Qn}{S^{1/2}}\right)^{0.4247}+0.7462$$

$$P_1=0.2686\left(\frac{Qn}{2S^{1/2}}\right)^{0.4247}+0.7462$$

(5-15) $$T_{nc}=\left[\left(\frac{F_{nc}W}{P_1}-0.275\right)\frac{1}{a}\right]^{1/b}$$

(5-16) $$T_{ic}=T_{nc}+T_{tc}$$

(5-17) $$T_{t_{ave}}=\left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}}-1\right)e^{(dL/QS^{1/2})}+1\right]\right]$$

(5-17a) $$T_{o_{adv}}=T_t-T_{t_{ave}}$$

(5-18) $$F_{(0\text{-}L)c}=[a\,(T_{ic}-T_{o_{adv}})^b+0.275]\,\frac{P_1}{W}+\left[\frac{(a(T_{o_{adv}})^b+0.275)\,(P-P_1)}{W}\right]$$

(5-19) $$F_{gc}=\frac{1.6041}{WL}\,(Q\,T_t+\frac{Q}{2}T_{nc})$$

(5-20) $$RO_c=F_{gc}-F_{(0\text{-}L)c}$$

(5-21) $$DP_c=F_{(0\text{-}L)c}-F_{nc}$$

(5-22) $$AE_c=100\,\frac{F_{nc}}{F_{gc}}$$

Design Example of Cutback-Inflow Equations

Information available:

Type: Graded furrow

Intake family: $I_f = 0.3$

Desired applied depth: $F_{nc} = 3.0$ in

Length: $L = 900$ ft

Slope: $S = 0.004$ ft/ft

Spacing: $W = 2.5$ ft

Roughness coefficient: $n = 0.04$

Procedure

(1) Assume inflow rate Q is 10 gpm.

(2) Find intake and advance coefficients for the 0.3 intake family from table 9:

$$a = 0.0364 \quad b = 0.7204 \quad c = 24.9706 \quad d = 9.1977 \times 10^{-4}$$

(3) Calculate advance time to the furrow length of 900 feet, using equation 2:

$$T_t = \frac{L}{c} e^{(dL/QS^{1/2})} = \frac{900}{24.9706} e^{\left[\frac{(9.1977 \times 10^{-4})(900)}{(10)\sqrt{0.004}}\right]}$$

$$T_t = 133.4 \text{ min}$$

(4) Calculate wetted perimeter plus constant P using equation 1 with a 10-gpm inflow rate:

$$P = 0.2686 \left(\frac{Qn}{S^{1/2}}\right)^{0.4247} + 0.7462$$

$$P = 0.2686 \left(\frac{10 \times 0.04}{\sqrt{0.004}}\right)^{0.4247} + 0.7462 = 1.33 \text{ ft}$$

P could be obtained from table 5-8 rather than by calculation.

(5) Calculate wetted perimeter plus constant P_1 using equation 1 with an inflow rate of Q/2 or 5 gpm:

$$P_1 = 0.2686 \left(\frac{5 \times 0.04}{\sqrt{0.004}}\right)^{0.4247} + 0.7462 = 1.18 \text{ ft}$$

(6) Calculate the net application time T_{nc} required for intake of the desired application (F_n) using equation 15:

$$T_{nc} = \left[\left(\frac{F_{nc}W}{P_1} - 0.275\right)\frac{1}{a}\right]^{1/b}$$

$$T_{nc} = \left[\left(\frac{3.0 \times 2.5}{1.18} - 0.275\right)\frac{1}{0.0364}\right]^{1/0.7204}$$

$$T_{nc} = 1{,}218 \text{ min}$$

(7) Calculate the inflow time (T_i) required using equation 16:

$$T_{ic} = T_{nc} + T_{tc} = 1{,}218 + 133 = 1{,}351 \text{ min}$$

(8) Calculate the average opportunity time $T_{t_{ave}}$ during the advance period using equation 17 and the initial inflow rate Q:

$$T_{t_{ave}} = \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]\right]$$

$$T_{t_{ave}} = \frac{1}{(24.9706)(900)\left[\frac{(9.1977 \times 10^{-4})^2}{10\sqrt{0.004}}\right]}$$

$$\left[\left(\frac{(9.1977 \times 10^{-4})(900)}{10\sqrt{0.004}} - 1\right)\right.$$

$$\left. e^{\left(\frac{(9.1977 \times 10^{-4})(900)}{10\sqrt{0.004}}\right)} + 1\right]$$

$$= 21.039[(1.3088 - 1)\, e^{1.3088} + 1]$$

$$= 21.039\ (2.143) = 45 \text{ min}$$

$$T_{oadv} = T_t - T_{t_{ave}}$$

$$= 133.4 - 45$$

$$= 88.4 \text{ min}$$

(9) Calculate the average intake (F_{0-t}) under cutback-inflow conditions using equation 18:

$$F_{(0-L)c}=[a\,(T_{ic}-T_{t_{ave}})^b+0.275]\,\frac{P_1}{W}+\left[\frac{(a\,T_{o_{adv}})^b+0.275)}{W}\right](P-P_1)$$

$$F_{(0-L)c}=[0.0364\,(1351-45)^{0.7204}+0.275]\frac{1.18}{2.5}+\left[\frac{0.0364\,(88)^{0.7204}+0.275}{2.5}\right](1.33-1.18)$$

$$F_{(0-L)c}=(3.15)+(0.476)\,(0.15)=3.2\text{ in}$$

(10) Calculate the gross application (F_g) using equation 19:

$$F_{gc}=\frac{1.6041}{WL}(Q\,T_{tc}+\frac{Q}{2}T_{nc})$$

$$F_{gc}=\frac{1.6041}{2.5(900)}\left[(10\times133.4)+(\frac{10}{2}\times1218)\right]$$

$$F_{gc}=5.3\text{ in}$$

(11) Calculate runoff (RO) using equation 20:

$$RO_c=F_{gc}-F_{(0-L)c}=5.3-3.2=2.1\text{ in}$$

(12) Calculate deep percolation (DP) using equation 21:

$$DP_c=F_{(0-L)c}-F_{nc}=(3.2-3.0)=0.2\text{ in}$$

(13) Calculate application efficiency (AE) using equation 22:

$$AE_c=100\frac{F_{nc}}{F_{gc}}=\frac{100\,(3.0)}{5.3}=57\%$$

(14) Summary of results:

I_f $=0.3$

Q $=10$ gpm

S $=0.004$ ft/ft

W $=2.5$ ft

F_n $=3.0$ in

L $=900$ ft

T_{ic} $=1{,}351$ min $=22.5$ hr

T_{tc} $=$ time to cutback $=133$ min $=2.2$ hr

RO_c $=2.1$ in

DP_c $=0.2$ in

AE_c $=57\%$

F_{gc} $=5.3$ in

(15) Assume different inflow rates and repeat steps 1–14 until either an acceptable inflow time or an application efficiency is obtained, or both.
Figure 5-19 illustrates design charts that simplify the design of cutback-inflow-furrow systems. The chart is for an intake family of 0.3, design application depth of 3.0 inches, and a slope of 0.004 ft per ft.

Level Impoundment Furrows

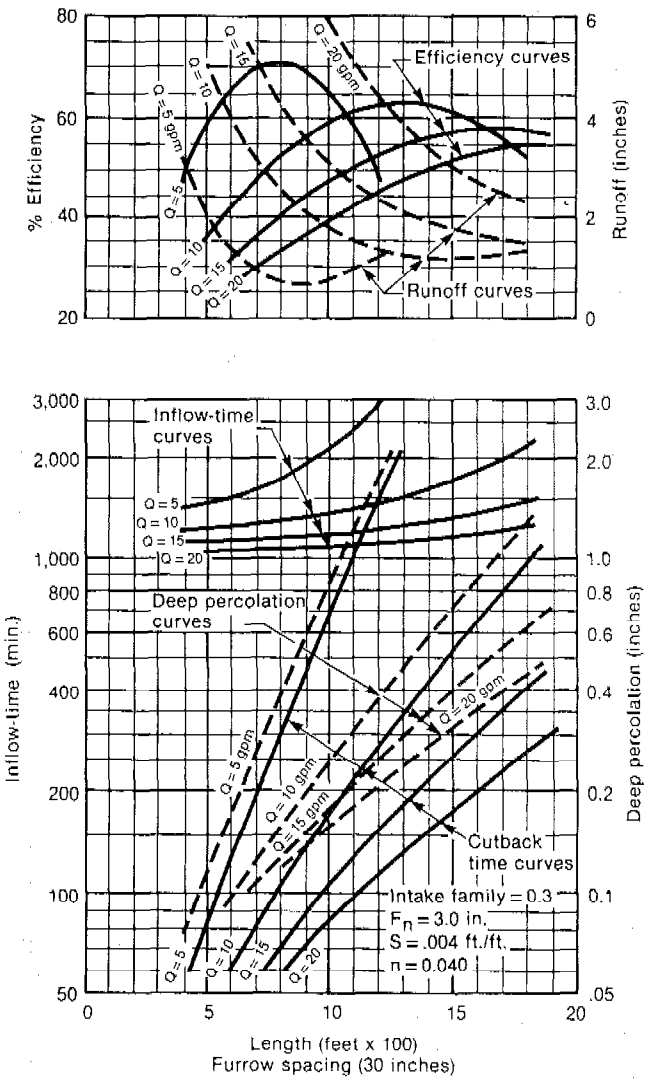
Surface runoff is eliminated in level furrow systems with diked ends. Water is applied at one end of the furrow at a rate that quickly provides coverage of the entire length, and is then ponded until it infiltrates the soil.

Design equation assumptions.—The design equations for level impoundment are based on the following assumptions:

1. The volume of water delivered to the furrow is equal to the average intake over the entire furrow length.
2. The intake opportunity time at the last point covered is equal to the time required for the net irrigation to enter the soil.
3. The longest intake opportunity time at any point along the furrow is such that deep percolation is not excessive.

Figure 5-19

Cutback-Inflow Furrow Design Chart



4. The ends of the furrows are blocked or diked to prevent outflow and the depth of flow can be contained within the furrow.

The gross application is determined by the inflow rate Q, inflow time T_i, furrow spacing W, and the length L as described by the equation:

$$F_g = \frac{1.6041\ Q\ T_i}{WL}$$

The gross application is also a function of the net application F_n and application efficiency AE as described by:

$$F_g = 100\ F_n/AE = \frac{100}{AE}(a\ T_n^b + 0.275)\frac{P}{W}$$

Substituting relationships for gross and net application yields an equation for application efficiency:

$$AE = \frac{100\ PL\ (aT_n^b + 0.275)}{(1.6041\ Q\ T_i)} \qquad (5\text{–}23)$$

The intake opportunity time at the end of the furrow, to meet assumption 2, is equal to the net intake opportunity time T_n. The average opportunity time for the furrow length is then the average opportunity time during advance time plus the net application time, or:

$$T_{o_{ave}} = T_t - \left[\frac{1}{L}\int_o^L T_t\right] + T_n$$

After integration of equation 2 for advance time (T_t) between the limits of 0 and L and dividing by L, the equation for average intake opportunity time becomes:

$$T_{o_{ave}} = T_n + T_t - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\right.$$

$$\left.\left[\left(\frac{dL}{QS^{1/2}} - 1\right) e^{(dL/QS^{1/2})} + 1\right]\right. \qquad (5\text{–}24)$$

where T_n, from equation 7, is:

$$T_n = \left[(F_n \frac{W}{P} - 0.275)\ 1/a\right]^{1/b}$$

The inflow depth for level furrows may be approximated by the empirical equation:

$$\text{Inflow depth} = 0.1116\ Q^{0.3419}$$

where Q is inflow rate in gpm.

The hydraulic gradient then becomes:

$$S = \frac{1}{L}(0.1116\ Q^{0.3419}) \qquad (5\text{–}25)$$

The first assumption is met by equating the gross application to the average intake:

$$F_g = \left[a(T_{o_{ave}})^b + 0.275\right]\frac{P}{W}$$

or

$$\frac{100}{AE}(a\,T_n{}^b + 0.275)\frac{P}{W} = \left[a(T_{o_{ave}})^b + 0.275\right]\frac{P}{W}$$

Solving for application efficiency yields the equation:

$$AE = 100\frac{(a\,T_n{}^b + 0.275)}{(a\,(T_{o_{ave}})^b + 0.275)} \qquad (5\text{–}26)$$

Combining the equations for efficiency, equations 23 and 26, yields the following equation for inflow time, T_i:

$$T_i = \frac{PL}{1.6041\,Q}\left[a(T_{o_{ave}})^b + 0.275\right] \qquad (5\text{–}27)$$

Deep percolation, expressed as an average for the furrow length (L) and spacing (W) is the difference between the gross and net application, or

$$DP = F_g - F_n \qquad (5\text{–}28)$$

Application efficiency is, as previously described:

$$AE = 100\frac{F_n}{F_g} = \frac{100\,F_n\,WL}{1.6041\,Q\,T_i} \qquad (5\text{–}13)$$

Table 5–10 illustrates design tables prepared using the level furrow relationships. Similar tables for selected net application depth (F_n), furrow length (L), and roughness coefficient (n) can be developed to facilitate design and managment of level furrows. Design charts also can be prepared.

Summary of Level Furrow Equations

Wetted perimeter plus constant

(5–1) $$P = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.7462$$

Inflow time

(5–27) $$T_i = \frac{PL}{1.6041\,Q}\left[(a(T_{o_{ave}})^b + 0.275)\right]$$

Average intake opportunity time

(5–24) $$T_{o_{ave}} = T_n + T_t - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]\right]$$

Net opportunity time

(5–7) $$T_n = \left[(F_n\frac{W}{P} - 0.275)\frac{1}{a}\right]^{1/b}$$

Advance time

(5–2) $$T_t = \frac{L}{c}\,e^{(dL/QS^{1/2})}$$

Hydraulic gradient

(5–25) $$S = \frac{1}{L}(0.1116\,Q^{0.3419})$$

Deep percolation

(5–28) $$DP = F_g - F_n$$

Gross application depth

(5–5) $$F_g = \frac{1.6041\,Q\,T_i}{WL}$$

Application efficiency

(5–13) $$AE = 100\frac{F_n}{F_g} = \frac{100\,F_n\,WL}{1.6041\,Q\,T_i}$$

Design Example of Level Furrows

Information Available:

Type: Level impoundment

Intake family: $I_f = 0.3$

Desired application depth: $F_n = 3.0$ in

Length: $L = 900$ ft

Spacing: $W = 2.5$ ft

TABLE 5–10.—*Level furrows*

			n=0.04 W=30 inches					
F_n (in)	L (feet)	I_r	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
3.0	600	0.1	5	80.9	693	.71	1,432	2,902
			10	97.3	288	.08	152	2,357
			15	98.5	189	.04	77	2,062
		.3	10	79.8	351	.76	368	712
			15	91.3	205	.29	131	630
			20	94.3	149	.18	81	575
			30	96.1	97	.12	51	501
			40	96.7	73	.10	41	453
			50	96.9	58	.10	36	417
		.5	10	47.9	585	3.26	897	399
			15	76.4	245	.92	224	354
			20	85.7	164	.50	117	324
			30	91.3	102	.29	63	284
			40	93.1	74	.22	47	258
			50	93.8	59	.20	40	238
			60	94.2	49	.18	36	223
		.75	15	50.8	368	2.91	440	223
			20	69.3	202	1.33	186	204
			30	82.7	113	.63	83	180
			40	87.0	81	.45	56	164
			50	89.0	63	.37	45	152
			60	90.0	52	.33	39	142
		1.00	20	50.2	279	2.97	297	147
			30	71.7	130	1.19	108	130
			40	79.6	88	.77	67	119
			50	83.2	67	.61	51	110
			60	85.1	55	.52	43	103
		1.50	30	48.7	192	3.17	188	86
			40	63.2	111	1.75	97	79
			50	70.7	79	1.24	67	72
			60	75.0	62	1.00		
		2.0	40	47.0	149	3.39	141	60
			50	57.8	97	2.19	87	56
			60	64.4	73	1.66	64	52
3.0	800	.1	10	90.2	415	.33	532	2,223
			15	96.1	260	.12	187	1,942
			20	97.5	192	.08	115	1,752
		.3	15	74.3	336	1.04	438	596
			20	85.2	220	.52	207	543
			30	91.6	136	.27	102	472
			40	93.6	100	.21	73	425
			50	94.4	78	.18	61	391

TABLE 5-10.—*Level furrows* (cont.)

				n=0.04	W=30 inches			
F_n (in)	L (feet)	I_f	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
		.5	15	41.6	599	4.20	1,023	336
			20	63.4	295	1.73	375	307
			30	80.4	165	.73	145	268
			40	85.9	109	.49	93	242
			50	88.4	85	.40	72	224
			60	89.6	70	.35	61	209
		.75	20	34.9	536	5.60	790	194
			30	61.6	202	1.87	227	170
			40	73.2	128	1.10	126	154
			50	78.6	95	.82	90	143
			60	81.6	76	.68	72	133
		1.00	30	42.7	292	4.03	354	123
			40	58.7	159	2.11	170	112
			50	67.4	111	1.45	112	104
			60	72.6	86	1.15	86	97
		1.50	40	34.0	275	5.82	315	75
			50	46.1	162	3.50	176	69
3.0	1,000	.1	15	90.1	346	.33	464	1,852
			20	94.5	247	.18	233	1,668
			30	96.8	161	.10	122	1,428
		.3	15	45.5	686	3.60	1,546	571
			20	67.5	346	1.44	544	518
			30	83.5	187	.59	203	450
			40	88.5	132	.39	128	404
			50	90.6	103	.31	98	371
		.5	20	34.6	675	5.66	1,270	293
			30	62.5	249	1.80	338	256
			40	74.4	157	1.03	181	231
			50	79.9	117	.75	127	213
			60	82.9	94	.62	101	199
		.75	30	36.3	430	5.27	641	162
			40	53.7	218	2.59	282	147
			50	63.7	147	1.71	175	135
			60	69.6	112	1.31	130	127
		1.00	40	35.3	331	5.51	440	107
			50	47.5	197	3.32	245	99
			60	55.7	140	2.39	168	93
3.0	1,200	.1	15	77.3	484	.88	1,184	1,780
			20	88.6	317	.39	480	1,600
			30	94.4	198	.18	204	1,367

TABLE 5-10.—*Level furrows* (cont.)

				n=0.04 W=30 inches				
F_n (in)	L (feet)	I_f	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
		.3	20	43.9	639	3.83	1,482	499
			30	70.7	264	1.24	406	432
			40	80.6	174	.72	220	388
			50	84.9	132	.53	155	356
			60	87.2	107	.44	124	331
		.5	30	41.4	452	4.25	805	246
			40	58.8	238	2.10	355	222
			50	68.3	164	1.39	222	204
			60	73.7	127	1.07	164	190
		.75	40	33.8	414	5.86	645	141
			50	46.5	242	3.46	347	130
			60	55.0	170	2.45	232	122
		1.00	60	38.4	243	4.81	332	89
4.0	600	.3	10	85.4	438	.68	368	1,086
			15	94.0	265	.26	131	963
			20	96.1	195	.16	81	880
		.5	10	56.7	660	3.06	897	599
			15	82.5	302	.85	224	533
			20	89.7	208	.46	117	489
			30	93.9	133	.26	63	430
			40	95.2	97	.20	47	391
		.75	15	59.4	420	2.74	440	332
			20	76.4	245	1.23	186	305
			30	87.4	143	.58	83	269
			40	90.7	103	.41	56	245
			50	92.2	81	.34	45	227
			60	92.9	66	.31	39	213
		1.00	15	35.3	705	7.32	864	237
			20	58.7	318	2.81	297	218
			30	78.3	159	1.11	108	193
			40	84.8	110	.72	67	176
			50	87.7	85	.56	51	164
			60	89.2	70	.49	43	154
		1.50	30	57.0	219	3.01	187	127
			40	70.9	132	1.65	97	116
			50	77.4	97	1.17	67	108
			60	81.0	77	.94	52	102
		2.00	30	36.7	339	6.89	329	96
			40	55.3	169	3.23	141	88
			50	65.8	114	2.08	87	82
			60	71.8	87	1.57	64	77

Roughness coefficient: $n=0.04$

Procedure:

(1) Assume inflow rate is 20 gpm
(2) Compute hydraulic gradient, using equation 25:

$$S=\frac{1}{L}(0.1116\ Q^{0.3419})$$

$$S=(0.1116\ (20)^{0.3419})/900=0.000345\ \text{ft/ft}$$

(3) Compute wetted perimeter plus constant, using equation 1:

$$P=0.2686\left[\frac{20\times 0.04}{\sqrt{0.000345}}\right]^{0.4247}+0.7462$$

$$P=2.07\ \text{ft}$$

(4) Find coefficients from table 5–9:

Intake family 0.3

$a=0.0364$ $b=0.7204$ $c=24.9706$
$d=9.1977\times 10^{-4}$

(5) Compute net opportunity time, using equation 7:

$$T_n=\left[\left(F_n\frac{W}{P}-0.275\right)\frac{1}{a}\right]^{1/b}$$

$$T_n=\left[\left(\frac{3.0\times 2.5}{2.07}-0.275\right)\frac{1}{0.0364}\right]^{1/0.7204}$$

$$T_n=532\ \text{min}$$

(6) Compute advance time, or the time water is predicted to reach the end of the furrow, using equation 2:

$$T_t=\frac{L}{c}e^{(dL/QS^{1/2})}=\frac{900}{24.9706}e^{2.228}=335\ \text{min}$$

(7) Compute average opportunity time, using equation 24:

$$T_{o_{ave}}=T_n+T_t-\left[\frac{1}{cL\left(\frac{d}{Q\sqrt{S}}\right)^2}\left[\left(\frac{dL}{Q\sqrt{S}}-1\right)e^{(dL/Q\sqrt{S})}+1\right]\right]$$

$$T_{o_{ave}}=532+335-\left(\frac{1}{(24.9706)(900)\frac{(9.1977\times 10^{-4})^2}{20\sqrt{0.000345}}}\right)\left[\left[\frac{(9.1977\times 10^{-4})(900)}{20\sqrt{0.000345}}-1\right]e^{\left[\frac{(9.1977\times 10^{-4})(900)}{20\sqrt{0.000345}}\right]}+1\right]$$

$$T_{o_{ave}}=532+335-7.26\ (1.228\ e^{2.228}+1)$$

$$T_{o_{ave}}=532+335-7.26\ (12.395)=777\ \text{min}$$

(8) Compute inflow time, using equation 27:

$$T_i=\frac{PL}{1.6041\ Q}(a\ (T_{o_{ave}})^b+0.275)$$

$$T_i=\frac{(2.07)(900)}{(1.6041)(20)}(0.0364\ (777)^{0.7204}+0.275)$$

$T_i=271$ min inflow time

(9) Compute gross application, using equation 5:

$$F_g=\frac{1.6041\ Q\ T_i}{WL}=\frac{1.6041\ (20)\ (271)}{(2.5)\ (900)}=3.9\ \text{in}$$

(10) Compute average deep percolation, using equation 28:

$$DP=F_g-F_n=3.9-3.0=0.9\ \text{in}$$

(11) Compute application efficiency, using equation 13:

$$AE = 100\frac{F_n}{F_g} = \frac{100\,(3.0)}{3.9} = 77\%$$

(12) Summary

$W = 2.5$ ft

$F_n = 3$ in

$L = 900$ ft

$I_f = 0.3$

$Q = 20$ gpm

$T_i = 271$ min

$F_g = 3.9$ in

$AE = 77\%$

$DP = 0.9$ in

$T_t = 335$ min

$T_n = 532$ min

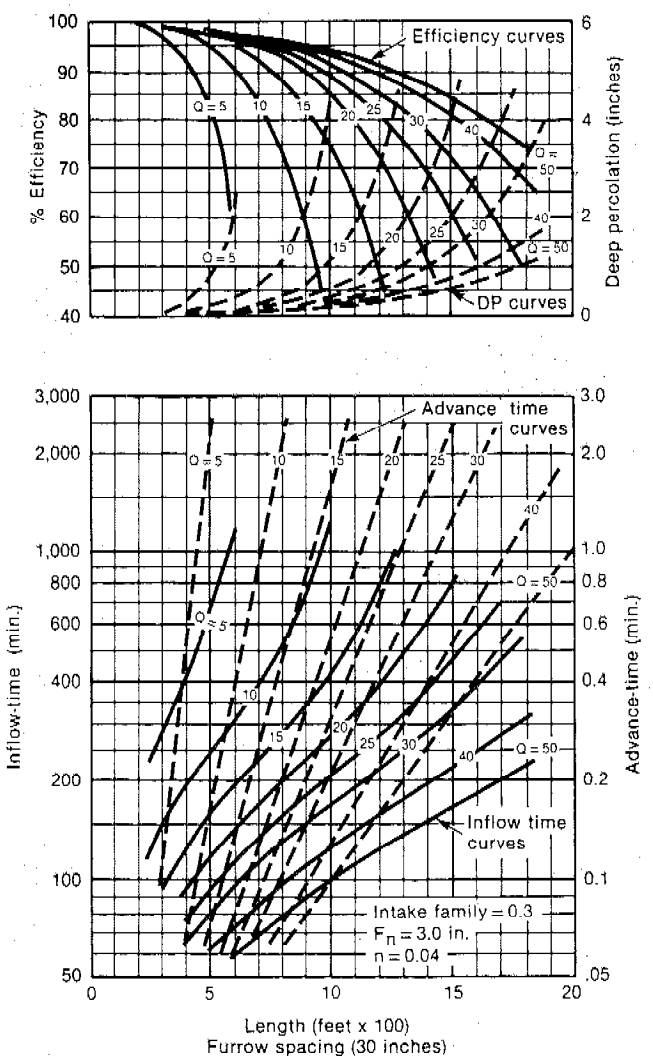
(13) Assume different flow rate and repeat steps 1–11 until an acceptable inflow time and/or efficiency is obtained.

The solution of equations may be avoided by use of design tables.

Preparation of design charts for selected values of intake family and net application depth, using hand calculators or computer facilities, is recommended to avoid the relatively laborious calculations involved. Figure 5-20 is a design chart for intake family 0.3 and a 3.0-inch net application depth.

Figure 5-20

Level Impoundment Furrow Design Chart



Distribution System

The onfarm water conveyance portion of a furrow or corrugation irrigation system consists of all the ditches, conduits, structures, and outlets necessary to deliver the water from the supply source to the individual furrows where it is to be applied. The water conveyance system should be located so that all sections are convenient for operation and maintenance. A properly designed underground pipeline requires the least maintenance and labor. The distribution system should be designed to:

1. Deliver the required quantity of water to each segment of the furrow or corrugation at an elevation that permits proper operation of the system.
2. Be accessible for operation and maintenance.
3. Be flexible in operation.
4. Convey the water as economically, efficiently, and safely as possible.
5. Not permit excess loss in transit.
6. Include facilities for water measurement.

The planned layout of the distribution system should be such that tailwater recovery can be readily incorporated when the system is installed. Other potential uses, such as distribution of livestock waste on the field, should also be considered when making the system layout.

Cost is a major factor in determining the kind of distribution system to use. It is also important in the system layout. The system should be planned so that

the minimum amount of ditch and/or pipeline services the entire area and so that the cost of supporting structures is minimal. The system includes either farm ditches or pipelines in conjunction with related structures for conveyance, grade control, water distribution, measurement, and application to the field.

Farm Ditch

Irrigation ditches are open channels used to carry irrigation water to or part way to its point of use. Small, inadequate ditches without proper control structures and maintenance probably cause more trouble in operating a furrow irrigation system than any other factor. In porous soils, unlined ditches lose considerable quantities of water by seepage. This loss frequently accounts for 25 percent or more of the water delivered to the conveyance system. Vegetation along a ditch contributes to water loss through transpiration. There is potential for damage to the distribution system if open ditches are located where they are accessible to livestock or to vehicular traffic. Open, unlined ditches in permeable soils can also cause waterlogged areas.

Lining is an effective way to control seepage and prevent ditch erosion. Concrete linings have proved the most satisfactory type over a period of years. Permanent ditches may, however, obstruct the use of farm equipment. Since the quantity of water needed for most farm irrigation systems is small enough to be carried in a pipeline, surface or underground pipe generally is recommended instead of surface irrigation ditches.

Pipelines

Irrigation pipelines can be placed on the surface or underground. Portable surface pipe has an advantage over underground pipe in that it can be moved and used in more than one location. The disadvantages are that labor is required to move the pipe and it is more susceptible to damage.

Pipeline delivery systems may consist of a combination of buried line and surface pipe. A buried main line may extend from the water source to individual fields and surface pipe may be used for the field main. This permits moving the surface pipe to other fields. The buried main can also extend into the fields as a field main and have risers and valves appropriately spaced to deliver water to surface ditches or gated pipe. The pipe size should limit the velocity to about 5 feet per second.

Related Conveyance Structures

If open ditch systems are used to deliver water to a furrow or corrugation system, frequently it is necessary to provide some type of structure to carry the water across depressions or drains and under roads or other obstructions. Flumes, inverted siphons, and culverts are the structures most commonly used.

Flumes.—Flumes are artificial channels supported by substructures that carry water across areas where ditches are not practical. They must be large enough to carry the full discharge of the ditch and the substructures must be strong enough to support the channel when it is filled with water.

Inverted siphons.—Inverted siphons are closed conduits that carry water under depressions, roads, or other obstructions.

Culverts.—Culverts are closed conduits installed at ditch grade and are commonly used to carry water under farm roads. They are usually corrugated metal, but they can also be concrete pipe.

Where the ditch grade is so steep that the design flow would have an erosive velocity, some protective structure, such as a drop spillway or pipe drop, must be used. These structures control ditch velocity by abruptly lowering the water level. A pipe drop has an advantage in that it can also serve as a ditch crossing.

Distribution Structures

Distribution-control structures are required for easy and accurate distribution of irrigation water to the various fields on a farm or to various parts of a field. They may consist of division boxes to divide or direct the flow of water between two or more ditches, checks that form adjustable dams to control the elevation of the water surface upstream so that water can be diverted from the ditch, or turnout structures to divert part or all of the irrigation stream to a selected portion of the irrigated area.

Application Control Structures

Various devices are used for controlling the flow of water into each furrow or corrugation. Since it is generally desirable to deliver nearly equal flows into a number of rows at one time, control is based on the hydraulic concept that outlets of equal size operating under the same pressure head have equal flows. Rates of flow are changed during the irrigation by altering the size of the outlets, varying the number of

outlets used, or changing the operating head over the outlets. The most common type of outlets used are siphon tubes or spiles for delivery from open ditches, and gates installed in sections of a pipe for delivery from surface or underground pipelines.

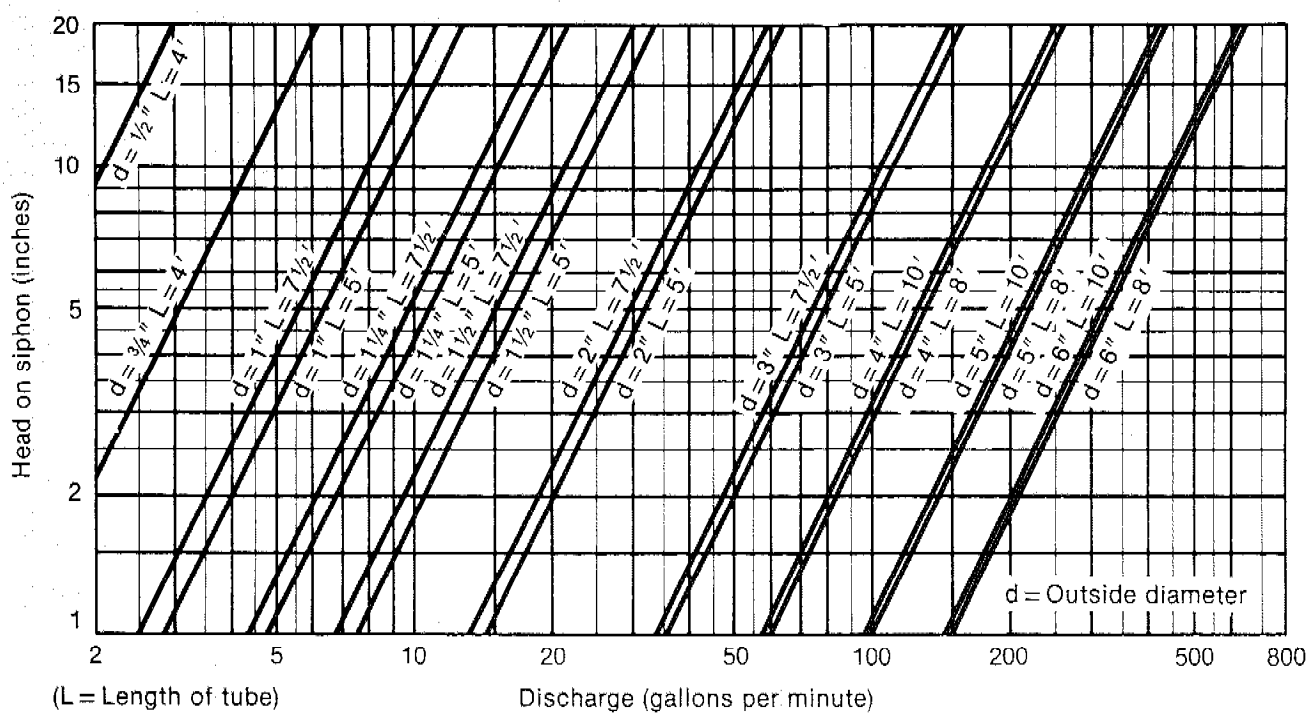
Siphon tubes.—Siphon tubes are usually aluminum or plastic pipe preformed to fit a half cross section of an irrigation ditch. Normal diameters used for furrow or corrugation irrigation range from 0.5 to 2.0 inches. Tubes are available in various lengths but normally are either 5.0 or 7.5 feet long. The discharge of a siphon tube depends on: (1) the inside diameter of the tube, (2) the length of the tube, (3) inside roughness, (4) number and degree of bends, and (5) the head under which the tube is operating. When the outlet end is submerged, the operating head is the difference in elevation between the water surfaces at the entrance and outlet ends of the tube. When water in the tube is flowing freely, the operating head is the difference in elevation between the water surface at the entrance and the center of the outlet end of the tube. Figure 5–21 can be used to estimate the flow from standard aluminum or plastic siphon tubes. When the water supply decreases or is interrupted, standard siphon tubes lose their prime. A siphon tube that automatically resumes operation after interruptions in the water supply is a labor-saving device and provides more safety in furrow water application.

Spiles.—Spiles are pipes, 1.0 to 2.5 inches in diameter, used to distribute water from a ditch into corrugations or furrows. They are set permanently in the bank of the head ditch, and they must be long enough to extend through the bank and linings, if any.

Care must be taken to install spiles at the proper elevation so that the same amount of flow enters all the rows being irrigated at the same time. Spiles are used where the head ditch is nearly level. The water elevation in each ditch section can then be controlled by a check. It should be high enough above the center of the spile opening to deliver the maximum design furrow stream. The water can then be lowered to a point at which the cutback stream flows through the spiles. Flow can also be controlled by gates at the inlet end.

Figure 5-21

Discharge of Aluminum Siphon Tubes at Various Heads



Gated pipe.—Gated pipes are portable pipes with uniformly spaced outlets for releasing irrigation water into individual furrows or corrugations. Gated pipe can be used in place of a head ditch at the top of a field, or it can be used in conjunction with the head ditch. It is well suited to use in place of an intermediate head ditch on fields too long to be irrigated in one length of run. This permits cultivation through longer rows since the pipe can be moved readily.

When connected to buried pipelines through hydrants, gated pipes allow the water to be conveyed in an enclosed system from the source to the head of the furrows or corrugations, thereby reducing seepage losses to a minimum. They also provide a convenient means of regulating flow. The gates provide positive control and are especially good if cutback streams are used. They may be slide gates covering either round or rectangular holes in the pipeline, or they may be round alfalfa-type valves or round butterfly valves in short sections of the properly sized tubing connected to the pipe. Flexible sleeves are frequently attached to the gates to aid in distribution and to minimize erosion at the inlet to the rows. Water flow can be regulated by the degree of gate opening.

High labor costs have caused many farmers to seek labor-saving devices for their irrigation enterprises. These irrigators are interested in some method of making their systems automatic or, at least, semiautomatic. The first requirement for automation of a furrow system is that it be properly designed, installed, and maintained. Systems can be completely automatic, with reset features and water sensors that detect the need for irrigation, turn on the water if from farm sources, correctly irrigate the field portion by portion, turn off the water when the irrigation is complete, and reset so that the system is prepared for the next irrigation.

Most automated farm systems are semiautomatic, with the irrigator deciding when irrigation is needed and delivering the irrigation water to the field. Delivery to a field is by surface ditches or by surface or underground pipelines. Where surface ditches are used, the head ditches are lined and have check gates that are tripped by the weight of accumulated water from a controlled rate of flow that slowly fills a container. The ditch must have a predetermined grade so that water is applied uniformly to the correct number of furrows at a proper design rate. The furrows can be irrigated by use of spiles through the ditch or by use of the fail-safe siphon tubes.

Automation is more commonly used with underground pipe in conjunction with surface gated pipe. Pneumatic valves in hydrants attached to the underground pipe control the flow to sections of gated pipe. These valves are usually controlled by a time clock that allows the irrigation to continue for a predetermined time, and diverts water to sequencing sets across the field or fields.

If farm irrigation systems are to be automated, the following requirements should be met:

1. The system should be such that failure of the automation does not result in excessive damage to the immediate farm, or to other property.
2. The system should be simple, reliable, and easily maintained.
3. It should be economically feasible.
4. It should operate at low cost.
5. It should irrigate the field efficiently and distribute water uniformly.
6. It should be capable of applying various depths of water according to seasonal plant needs.

It is essential that any automatic or semiautomatic system include provisions for tailwater recovery.

The irrigation water can also be controlled by using sensing or timing devices that change the irrigation from one set of furrows to the next by automatically controlling gates or valves in the distribution system. Moisture resistance blocks and tensiometers are used as sensing devices. Tensiometers can be used only where soil moisture tensions are less than one atmosphere. The resistance blocks can measure a greater range of soil moisture conditions and, therefore, are probably more satisfactory for most uses.

Provisions to remove water promptly and safely from the irrigated land should be an integral part of the design of a farm irrigation system. The excess water may be surface runoff from rainfall, tailwater from irrigation, or excess percolation of either irrigation or rainfall. It may also include leakage or seepage from parts of the conveyance system.

Storm runoff must be diverted around or carried through the irrigation system to protect the land, the irrigation system, and the crop. Special erosion control measures may require modifications in the design or layout of the irrigation system. Tailwater from irrigation must be recovered or disposed of without damage to lower lands. Excess percolation of either irrigation water or rainfall may lead to a high water table that restricts root growth or promotes a saline or alkaline condition. Seepage from ditches, reservoirs, and sumps may waterlog adjacent land, requiring tile or open drains to control the water table.

Outflow Control

Rainfall Runoff

Standard Soil Conservation Service procedures are available to determine the volume and rate of runoff from precipitation. Runoff can leave the land through natural water courses. Tailwater or waste ditches are needed at the lower end of irrigation runs to collect both this rainfall runoff and tailwater from irrigation. Storm runoff generally governs the capacity requirements. Where storage and tailwater recovery facilities are provided for irrigation, the storm runoff should bypass the storage reservoir to prevent rapid loss of storage capacity by silt carried in the storm runoff.

Irrigation Runoff

Provisions for storage, safe disposal, or recovery of tailwater must be included in any graded furrow or corrugation irrigation layout if efficient irrigation is to be achieved. To obtain good water distribution in a furrow or corrugation system, the advance time should be as rapid as is practical. This requires an initial furrow stream considerably larger than needed to meet the intake rate of the soil, which results in considerable outflow or tailwater. By use of an inflow-cutback procedure, the tailwater can be

reduced. The irrigation tailwater must be collected and reused on the farms or disposed of safely in accordance with state requirements. Some states now require that irrigation water not be allowed to trespass on lands not under the control of the irrigator. It is then necessary to provide some means of collecting the tailwater, transporting it to a pit or reservoir, and either storing or providing recovery facilities as needed.

Subsurface Drains

Irrigation water applied plus effective precipitation usually exceeds crop evapotranspiration. Most of the excess water percolates below the root zone, and unless the underlying material is sufficiently permeable to allow penetration below drainage depth, a water table may form a few feet below the soil surface and require drainage facilities. If drainage facilities are needed, the water table must be held below the root zone to provide aeration and to control salinity. This control is accomplished by subsurface drains that intercept or accumulate the excess ground water and return it to the surface. Subsurface drains are normally designed to lower and maintain the water table at a level ranging from 4.0 to 8.0 feet below the ground surface. A subsurface-drainage system may consist of interceptor drains, relief drains, or pumped drains.

Interceptor drains.—Interceptor drains are used on the more sloping areas with a high water-table gradient. They are aligned perpendicular to the direction of ground-water flow. Subsurface drains are commonly used because the drain must be located according to ground-water conditions, which generally do not correspond to field boundaries, fences, or property lines.

Relief drains.—Relief drains are generally used on level to gently sloping areas with a low water-table gradient. They are usually aligned parallel to the direction of ground-water flow. Relief drains are usually planned as a series of lateral tile lines in a gridiron or herringbone pattern in which each line is connected to a main that leads to an open drain.

Pumped drains.—Pumped drains are used in areas in which the soils are underlain by porous sand or gravel aquifers that can be lowered by pumping. Detailed subsurface and ground-water studies are required to determine the possibility of satisfactorily lowering the water table by pumping.

Tailwater Recovery

Recovery or recirculating facilities collect irrigation runoff and return it to the same or adjacent field for irrigation use. Such systems can be classified according to the method of handling runoff or tailwater. If the water is returned to a field lying at a higher elevation, it is usually referred to as a return-flow system; if the water is applied to a lower lying field, this is termed sequence use. The components consist of tailwater ditches to collect the runoff, drainageways or waterways to convey water to a central collection area, a sump or reservoir for water storage, a pump, a power unit, and a pipeline or ditch to convey water for redistribution. Under certain conditions where gravity flow can be used, neither pump nor pipeline may be necessary.

A return-flow system provides for the temporary storage of a given amount of water and includes the pumping equipment and pipeline needed to deliver the water back into the application system. The sequence system generally has a pump and only enough pipe to convey the water to the head ditch of the next field. The farm often can be planned so that there is enough elevation difference between fields to apply the runoff water to a lower field in sequence by gravity. Recovery systems can also be classified according to whether they accumulate and store runoff water. Systems storing collected runoff water are referred to as reservoir systems. Systems that immediately return the runoff water require little storage capacity. They have automatically cycled pumping systems and are called cycling-sump systems. One or more types of systems may be applicable to a given farm. A sump is used where land value is high, water cannot be retained in a reservoir, or water ponding is undesirable. Dugouts or reservoirs are more common and are easily adapted to storage and planned recovery of irrigation tailwater.

A reservoir system collects enough water to be used as an independent supply or as a supplement to the original supply. The reservoir size depends on whether collected water is handled as an independent supply and, if not, on the rate water is pumped for reuse. A smaller reservoir is required if the system is used for cutback irrigation. Reservoirs should be at least 8.0 and preferably 10 feet deep to discourage growth of aquatic weeds. Side slopes should be 2 or 2.5 feet horizontal for each 1 foot

vertical to prevent sloughing of the banks. Where dugouts may be a safety hazard, one end slope should be 5 to 1 or less to provide a way of escape in case of accidents. The reservoir should provide for an unused storage depth of at least 1.0 foot.

The cycling-sump system consists of a sump and a pump large enough to handle the expected rate of runoff that enters the sump. The sump is generally a vertical concrete or steel tube with a concrete bottom. The tube is approximately 48 inches in diameter and installed to a depth of approximately 10 feet. Pump operation is controlled automatically by a float-operated or electrode-operated switch. Some storage can be provided in the collecting ditch.

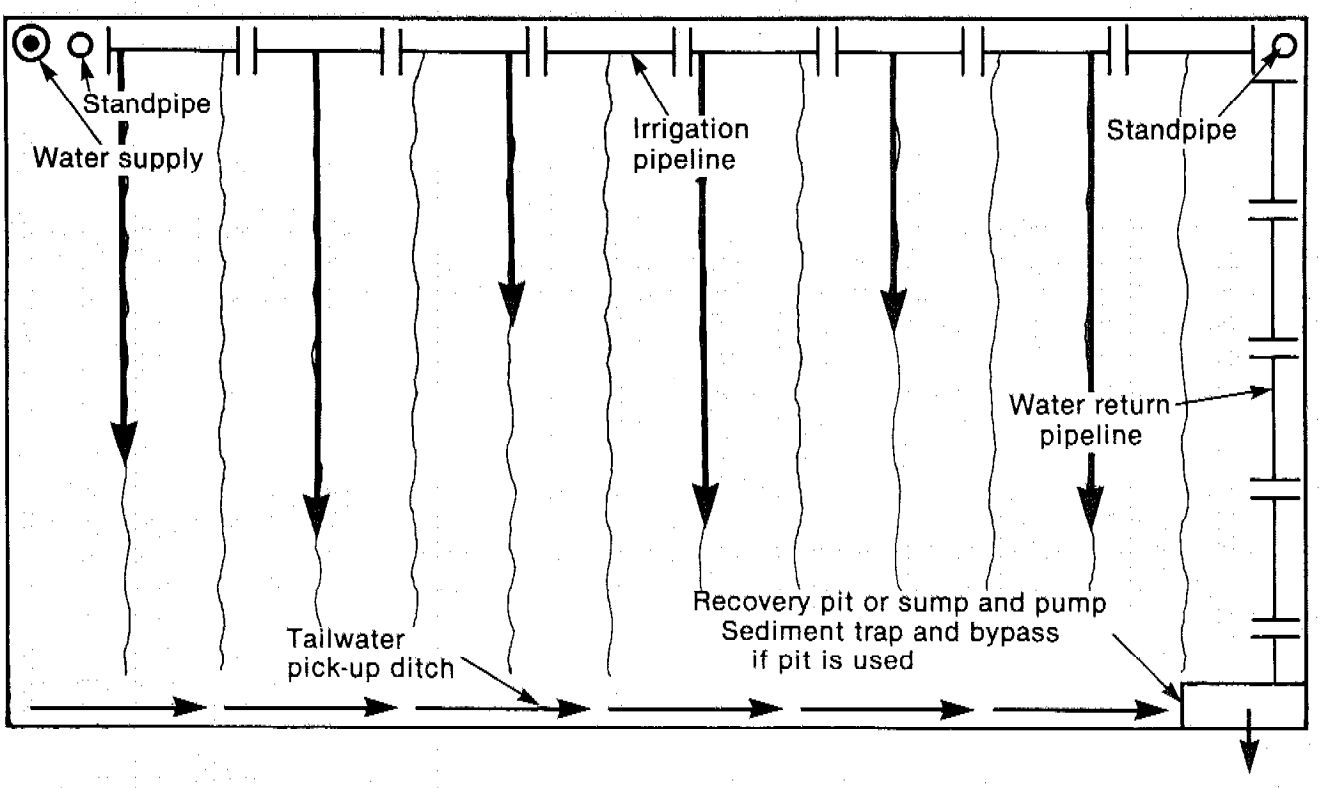
The size, capacity, location, and selection of equipment for these systems are functions of the main irrigation system, the topographic layout of the field or fields, and the farmer's irrigation practice and desires (fig. 5–22).

If a sump is used, the pump should be capable of pumping 40 percent of the initial water supply. This system has the disadvantage that water is applied intermittently, making efficient application rather difficult.

When a dugout is used, it should have the capacity to store the tailwater from a complete irrigation set. The pump capacity depends on the method or schedule of reuse planned. The pump can be designed to empty the storage in approximately one-fourth to one-third the desired application time and, in this way, provide a cutback operation, or it can be designed for continuous operation after the first set is completed with additional furrows watered after the first set.

Figure 5-22

Plan for a Return-Flow System Used in Conjunction With an Underground Pipeline Distribution



There are two purposes for making a furrow intake evaluation. The first is to aid in placing a named soil or group of soils in the intake family for design purposes. The second is to determine the intake time relationship for the specific conditions on an individual farm.

Identifying the furrow intake family associated with a soil series and placing it into an irrigation design group may require evaluations on only a few representative sites in an area. To determine a design criterion adequate for irrigation under the specific conditions on an individual farm, an evaluation must be made on a specific field under a given set of conditions. Recommendations can then be made as to management adjustments needed.

In making an evaluation, inflow and outflow measurements representing an entire irrigation set are most desirable. An alternative is to measure inflow and outflow for the first one-fourth to one-half of the irrigation set. If all irrigations during the season cannot be measured, it is best to make the furrow-intake evaluations during the middle of the irrigation season when conditions are about average; intake rates are usually high in the early part of the irrigation season and lower toward the end of the season.

Site Selection

Furrow tests to determine the intake characteristics must be made on carefully selected sites representative of the soil being evaluated. The site should have no recognizable difference in soils throughout the length that is to be evaluated. The furrows should have a uniform cross section and a uniform grade between the inflow and outflow measuring points. Individual wheel rows should not be evaluated, but they may be included when evaluating a group of furrows.

At least three adjacent furrows or furrow groups should be measured on each test site. Adjacent furrows on each side of the test area should also be irrigated simultaneously.

Soil Conditions

Onsite estimates of soil moisture are essential and should be made when evaluating a specified field. Where feasible, studies should be made if moisture conditions indicate that a normal irrigation application is needed. The condition of the furrows (freshly cultivated, cloddy, dispersed soil, smoothed by previous irrigation, etc.) should be recorded because they influence furrow intake rates. The number of times the field has been irrigated during the season should also be recorded.

Cropping History

The present crop, stage of growth, and previous crop grown should be recorded.

Flow Measurements

The flow of water in furrows can be measured in several ways. If the flow is small (up to about 20 gpm), inflow can be measured volumetrically with a calibrated container and stop-watch, or with other small measuring devices (e.g., orifice plates, V-notch weirs, or trapezoidal flumes). Outflow can be measured with any of the above small measuring devices. See NEH Section 15, Chapter 9, "Measurement of Irrigation Water," for additional information. Care should be taken in selecting and installing measuring devices so as not to block the furrow flow. The outflow measuring device should be located at a point where backwater does not affect the flow to the extent that false intake rates are measured.

Flow Control

The inflow rate should be constant throughout the test. Otherwise, the volume of water in channel storage in the furrow also changes. The inflow rate throughout the test must be described by measured flow rates and the time of measurement.

Procedures

Measure, do not estimate, the furrow length between the inflow and outflow measuring stations. Evaluate the full furrow length. The minimum evaluation length should be 200 to 300 feet for high-intake-rate soils, and 500 to 600 feet for low-intake-rate soils. Determine the average furrow slope and cross section. Take readings to determine uniformity of grade. Adequate cross section measurements usually can be obtained by measuring down from a straight edge placed level across the ridges. Measure cross sections at representative locations (usually two or three) in each test furrow or

furrow group. Locate flow-measuring stations at intervals of 50 to 100 feet along the furrow. The furrow stream introduced should not cause erosion. It is, however, desirable, as part of the evaluation, to use the same flow rate that the farmer normally uses, even if it results in erosion. The minimum flow should be large enough to produce a fairly uniform rate of advance. As shown in figure 5-24, record the time water starts flowing into each furrow. Adjust streams so that flows into all furrows are approximately equal. Record the time at which the water in each furrow reaches each station. Periodically or when the inflow rate changes, measure the inflow stream and record the rate of flow and the time. Record the time at which water starts to flow through the outflow measuring device. Periodically measure and record the outflow. If ending the intake evaluation before completion of the full irrigation, record final inflow-outflow measurements and the maximum depth of flow.

Although not needed for the intake evaluation, for the field evaluation it is desirable to measure the wetted bulb after the completed irrigation. A soil moisture probe will readily define the boundary line between the wet soil and the relatively dry soil. The intake opportunity time needed to obtain this wetted pattern should be included with the sketch of the bulbs. Another method that can be used is to excavate a trench across the furrow and observe the wetted area. Examples of data collected from a field trial are given on the furrow intake-data sheets (figs. 5-23, 5-24, and 5-25).

Computation and Evaluation

Compute the inflow and outflow volumes. For each furrow or groups of furrows, determine the average inflow (Q_1), the inflow time (T_1), and the cumulated volumes of inflow (v_1) and outflow (v_0) at the end of the irrigation and at selected intermediate times. The first intermediate time selected should be after flow has reached the outflow station, flow is reasonably uniform, and surface storage in the furrow reach is stable. For each furrow, determine a minimum of three points on the cumulative intake vs. time line. Each point is described by the coordinates: (1) cumulative intake for the furrow length (F_{ave}), and (2) the average opportunity time for intake in the furrow length (T_o).

The average intake ($F_{(0-L)}$) is determined using the following equation:

$$F_{(0-L)} = \frac{1.604}{L(P)}(v_{in} - v_{out} - v_s) = \text{in}$$

where

v_{in} = volume of inflow, gal

$= Q_1 \times T_1$

Q_1 = average inflow rate, gpm

T_1 = inflow time, min

v_{out} = volume of outflow, gal

$= Q_2 \times T_2$

Q_2 = average outflow rate, gpm

T_2 = outflow time, min

v_s = surface storage in gallons in evaluation length, L

L = evaluation length, feet (distance between inflow and outflow measuring stations)

P = width over which intake occurs, equal to wetted perimeter plus a constant

The intake width (P) can be determined using the following:

$$P = 0.2686(Q_1 n / S^{0.5})^{0.4247} + 0.7462 = \text{ft}$$

where

n = Manning coefficient of roughness

S = furrow slopes, ft/ft

Surface storage (v_s), in lieu of actual measurements, can be estimated by the following:

$$v_s = L\,[0.09731(Q_1 n / S^{0.5})^{0.7527} - 0.00574] = \text{gal}$$

The average opportunity time (T_o), in minutes, may be determined as the average of the inflow time (T_1) and the outflow time (T_2).

or: $T_o = 0.5\,(T_1 + T_2)$

When the advance is curvilinear, a more exact value of average opportunity time can be obtained by averaging the opportunity time at various points

FURROW INTAKE

Owner J. Walker State Idaho County Payette

Legal Description Section 1, T7N R4W Date 7/12/78

Soil Series Moulton sandy loam Cylinder Family 1.0
(Attach Soils 232 Card)

Tilth Good Compaction Moderate

Surface Condition Firm

Crop Corn Stage of Growth 48 inches Previous Crop Corn

Tillage Practices Shovel type cultivator

Date Last Irrigation 6/13/78 Inches Applied $\frac{(1.6041)(14.09)(480)}{(900)(2.5)} = 4.82$ gross

Rainfall Since Irrigated: Date — Amount none

This is the Second (Pre: 1st, 2nd, etc.) Irr. of Crop

Additional Observations Flows were erosive at upper end

Normal Irrigating Time (inflow) 8 hours

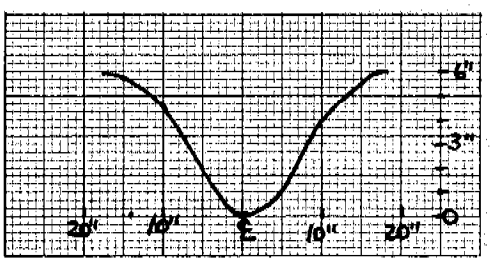
Furrow Spacing 30 Inches Furrow Length 900 Feet

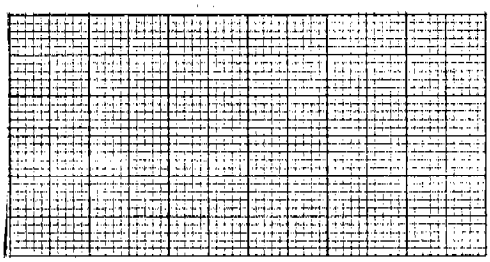
Furrow Profile: Furrow No. 1

Station	0+00	1+00	2+00	3+00	4+00								
Rod Reading	8.4	9.0	9.3	9.5	9.6								

Furrow Cross Section: Sketch or Rod Readings

Station 1+00 Station





Furrow Data Summary:

Q_1 (gpm)	T_1 (min.)	Q_2 (gpm)	T_2 (min.)	L (feet)	S (ft/ft)	W (feet)
14.09	480	8.48	361	900	0.003	2.5

Trial Furrow Intake Family (I'_f) 0.50

Figure 5-23.—Furrow-intake data sheet.

along the furrow length or by integration of the advance curve.

Computation of the opportunity time is facilitated by converting the 24-hour clock time used to record the time of measurements to decimal hours. For example, the 24-hour clock time of 1120 would become 11.33 (11+20/60).

If simultaneous measurements of flow are not made, a plot of cumulative inflow and outflow in gallons vs. clock time from the start of irrigation makes it easier to determine the intake volume at any elapsed time. Subtracting the cumulative outflow from the cumulative inflow yields the intake and storage. Subtracting the surface storage yields the volume of intake, in gallons, at any time. This is illustrated in figure 5-26.

The cumulative intake ($F_{(0-L)}$) and associated opportunity time (T_o) points, when plotted on log-log paper, define the measured intake line. This line is then compared to the intake-family lines (fig. 5-15) to determine the most representative intake family. This is illustrated on figure 5-26, examples 1 and 2.

Example 1

Determination of furrow-intake family from trial measurements where the total irrigation is measured (using example set of data as contained in furrow-intake data sheet).

Soil: Moulten sandy loam

$L=900$ ft $\quad W=2.5$ ft

$S=0.003$ ft/ft $\quad Q_1=14.09$ gpm

$P=(0.2686)(14.09\times 0.04/0.003^{0.5})^{0.4247}+0.7462$

$P=1.47$ ft

$v_s=900\ [(0.09731)(14.09\times 0.04/0.003^{0.5})^{0.7527}-0.00574]$

$v_s=500$ gal

Plotting points

$T_o=0.5\times 60$ min/hr [inflow time (hr)−outflow time (hr)]

$$aT_o^b+c=\frac{1.6041}{\text{Length}\times P}[\text{inflow vol (gal)}-\text{outflow volume (gal)}-\text{surface storage (gal)}]$$

Intake at 1701 hours

$$T_o=0.5\times 60\ [(16.5-8.5)+(17.0-11.0)]=420 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(6764-3060-0)=4.49 \text{ in}$$

Intake at 1430 hours (14.5)

$$T_o=0.5\times 60\ [(14.5-8.5)+(14.5-11.0)]=285 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(5090-1771-500)=3.42 \text{ in}$$

Intake at 1330 hours (13.5)

$$T_o=0.5\times 60\ [(13.5-8.5)+(13.5-11.0)]=225 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(4235-1212-500)=3.06 \text{ in}$$

Intake at 1230 hours (12.5)

$$T_o=0.5\times 60\ [(12.5-8.5)+(12.5-11.0)]=165 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(3380-666-500)=2.68 \text{ in}$$

Plot cumulative intake vs. opportunity time (aT_o^b+c vs. T_o) as in figure 5-26 and find intake family (I_f) equals 0.5. Equivalent application depth is:

$$F_{900}=4.49\times 1.47/2.5=2.65 \text{ in}$$

Furrow Flow Data

Sheet 1 of 2
Date 4/5/78
By [illegible]

Farm J. Walker SCD or SWCD Payette

Legal Description Sec. 1, T7N, R4W

Furrow No. 1 Station 0+00 Inflow X or Outflow

Measuring Device 1.5" Orifice free flow

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time Clock Time	(10) Elapsed Time (min)	(11) Station (ft)
0830	0			0				0841	11	2+00
		5			6.31	31.52	31.52			
0835	5			12.61				0857	27	4+00
		5			13.42	67.10	98.6			
0840	10			14.23				0914	44	5+00
		20			14.25	285.0	383.6			
0900	30			14.27				0932	62	6+00
		60			14.28	856.8	1240.4			
1000	90			14.29				0955	85	7+00
		60			14.27	856.2	2096.6			
1100	150			14.25				1024	114	8+00
		120			14.26	1711.2	3807.8			
1300	270			14.27				1100	150	9+00
		180			14.25	2565.0	6372.8			
1600	450			14.23						
		25			14.22	355.6	6728.4			
1625	475			14.22						
		5			7.11	35.6	6764.0			
1630	480			0						
					$Q_i = \frac{6764}{480} = 14.09$ gpm					

*24 hour clock time

Figure 5-24.—Furrow-intake evaluation—flow data example 1.

Example 2

Determination of furrow-intake family from trial measurements where only part of the irrigation is measured (using example set of data as contained on furrow-intake data sheets, figs. 5-27, 5-28).

Soil: Moulten sandy loam

$L = 400$ ft $\quad W = 2.5$ ft

$S = 0.003$ ft/ft $\quad Q_i = 14.12$ gpm

$P = (0.2686)(14.12 \times 0.04/0.003^{0.5})^{0.4247} + 0.7462$

$P = 1.47$ ft

$v_s = 400[(0.09731)(14.12 \times 0.04/0.003^{0.5})^{0.7527} - 0.00574]$

$v_s = 222.9$ gal

Plotting points

$T_o = 30$ [inflow time (hr) − outflow time (hr)]

$aT_o^b + c = \frac{1.6041}{\text{Length} \times P}$ [inflow vol (gal) − outflow vol (gal) − surface storage (gal)]

Furrow Flow Data

Sheet 2 of 2
Date 4/5/78
By ZVC

Farm J. Walker SCD or SWCD Payette

Legal Description Sec. 1, T 7N R

Furrow No. 1 Station 9+00 Inflow _____ or Outflow X

Measuring Device _____

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time Clock Time	(10) Elapsed Time (min)	(11) Station (ft)
1100	0			0						
		10			2.14	21.4	21.4			
1110	10			4.28						
		20			6.32	126.4	147.8			
1130	30			8.36						
		60			8.63	517.8	665.6			
1230	90			8.90						
		60			9.10	546.0	1211.6			
1330	150			9.30						
		120			9.32	1118.4	2330.0			
1530	270			9.34						
		60			9.34	560.4	2890.4			
1630	330			9.34						
		10			8.64	86.4	2976.8			
1640	340			7.93						
		21			3.96	83.2	3060.0			
1701	361			0						

$Q_2 = \frac{3060}{361} = 8.48$ gpm

*24 hour clock time

Intake at 1330 hours

$$T_o = 0.5 \times 60\,[(13.5-8.5)+(13.5-8.95)] = 286.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(4235.6 - 2721.6 - 222.9)$$
$$= 3.52 \text{ in}$$

Intake at 1230 hours

$$T_o = 0.5 \times 60\,[(12.5-8.5)+(12.5-8.95)] = 286.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(3380 - 2034 - 222.9)$$
$$= 2.97 \text{ in}$$

Intake at 1200 hours

$$T_o = 0.5 \times 60\,[(12.0-8.5)+(12.0-8.95)] = 196.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(2921 - 1691.9 - 222.9)$$
$$= 2.75 \text{ in}$$

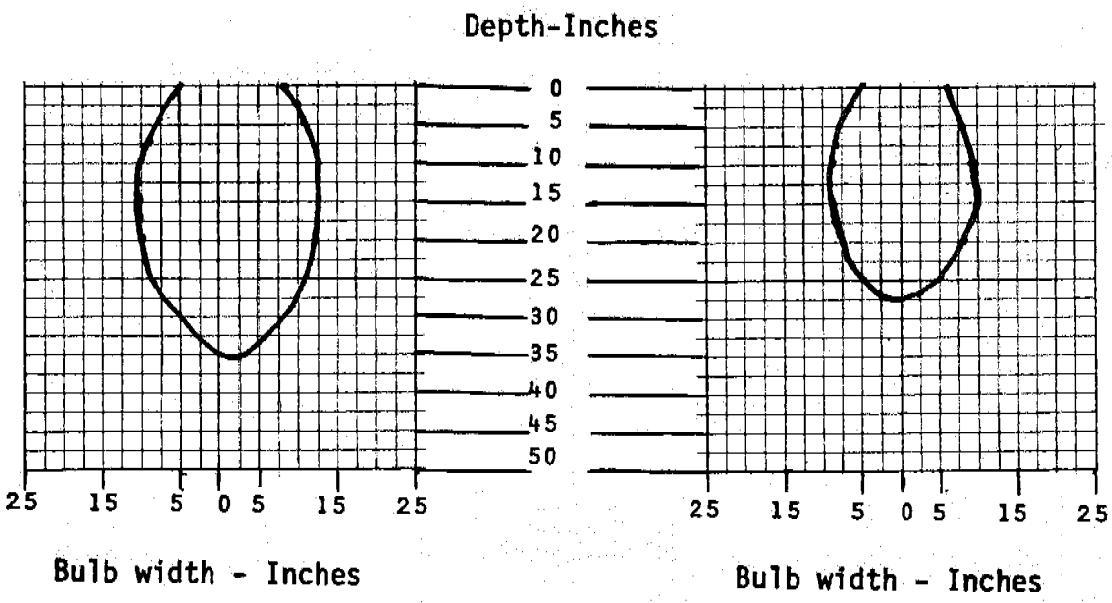
Estimated Moisture Condition

Furrow No. 1

Soil Depth Ft.	Station 0+20				Station 3+80				Station ___			
	Soil Texture	Water Holding Capacity	Percent Remaining	Amount To Be Applied	Soil Texture	Water Holding Capacity	Percent Remaining	Amount To Be Applied	Soil Texture	Water Holding Canacity	Percent Remaining	Amount To Be Applied
0-1	sl	1.4	25	1.05	sl	1.4	30	0.98				
1-2	s.l	1.8	50	.90	s.l	1.8	60	0.72				
2-3	s.l	1.8	75	.45	s.l	1.8	80	0.36				
3-4												
Totals				2.4				2.06				

Wetted Bulbs Sketch:

Station 0+50 Station 3+50

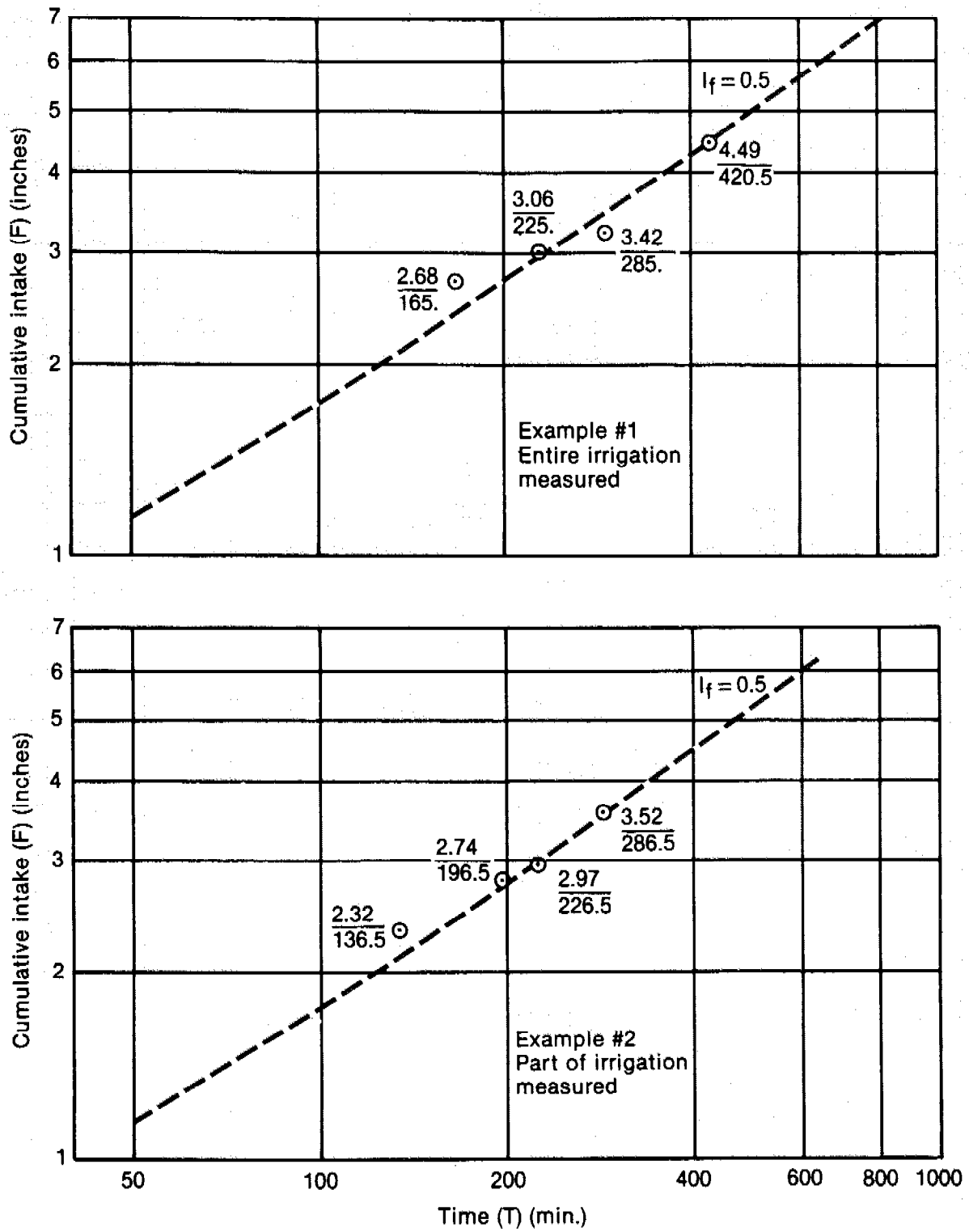


Time Bulbs Measured 24 hours after irrigation

Figure 5-25.—Furrow-intake evaluation—soil water.

Figure 5-26

Cumulative Intake vs. Time—Evaluation Examples



Furrow Flow Data

Sheet 1 of 2
Date 4/15/78
By TWC

Farm J. Walker SCD or SWCD Payette

Legal Description Sec 1, T7N R4W

Furrow No. 1 Station 0+00 Inflow X or Outflow

Measuring Device 1.5" Orifice - free flow

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time Clock Time	(10) Elapsed Time (min)	(11) Station (ft)
0830	0			0				0841	11	2+00
		5			6.31	31.52	31.52			
0835	5			12.61				0857	27	4+00
		5			13.42	67.10	98.62			
0840	10			14.23						
		20			14.25	285.0	383.6			
0900	30			14.27						
		60			14.28	856.8	1240.4			
1000	90			14.29						
		60			14.27	856.2	2096.6			
1100	150			14.25						
		120			14.26	1711.2	3807.8			
1300	270			14.27						
		30			14.26	427.8	4235.6			
1330	300			14.25						

$Q_1 = \frac{4235.6}{300} = 14.12$ gpm

*24 hour clock time

Figure 5-27.—Furrow intake evaluation—flow data example 2.

Intake at 1100 hours

$$T_o = 0.5 \times 60\,[(11.0-8.5)+(11.0-8.95)] = 136.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(2096.6 - 1022.9 - 222.9)$$
$$= 2.32 \text{ in}$$

Plot cumulative intake ($aT_o^b + c$) vs. opportunity time (T_o) as in figure 5-15 and find intake family equals 0.5.

Furrow Flow Data

Sheet 2 of 2
Date 4/15/78
By HBC

Farm J. Walker SCD or SWCD Payette

Legal Description Sec 1, T 7N R 4W

Furrow No. 1 Station 4+00 Inflow _____ or Outflow X

Measuring Device 1.5" orifice - free flow

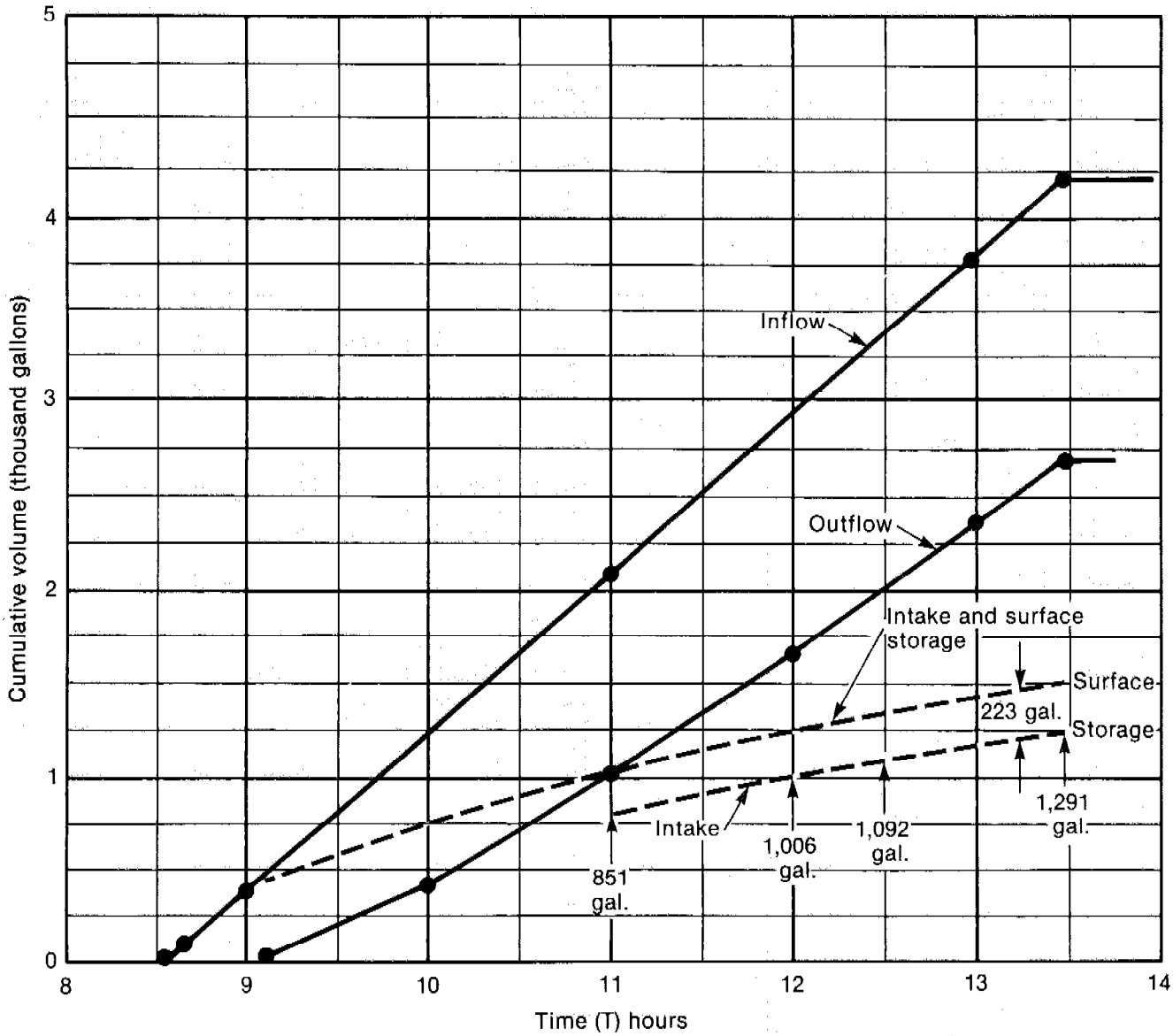
(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time Clock Time	(10) Advance Time Elapsed Time (min)	(11) Advance Time Station (ft)
0857	0			0						
		10			2.57	25.7	25.7			
0907	10			5.14						
		53			7.28	386.1	411.8			
1000	63			9.43						
		60			10.18	611.1	1022.9			
1100	123			10.94						
		60			11.15	669.0	1691.9			
1200	183			11.36						
		60			11.42	684.9	2376.8			
1300	243			11.47						
		30			11.50	344.8	2721.6			
1330	273			11.52						

$$Q_2 = \frac{2721.6}{273} = 9.97 \text{ gpm}$$

*24 hour clock time

Figure 5-28

Cumulative Inflow, Outflow, and Intake—Evaluation Example 2



Many terms used in irrigation work are frequently interpreted differently by personnel working in the irrigation field. The following definitions explain these terms as they apply to furrow irrigation.

Adequacy Terms

The following terms are useful for describing the adequacy of a given irrigation or series of irrigations.

Adequate Irrigation. An irrigation that replaces the management-allowed deficiency (MAD). Where MAD is equal to soil water deficiency (SWD), an adequate irrigation is also a full irrigation.

Full Irrigation. An irrigation that brings the entire root zone to field capacity (FC). After a full irrigation, the soil water deficiency (SWD) will be equal to zero in all parts of the field.

Efficiency Terms

The following efficiency terms are useful in evaluating the potential and/or actual effectiveness of irrigation water applications by a given system. The definitions are usually expressed in equivalent depths of free water (volumes per unit area).

Application Efficiency (AE). The ratio of the average depth of the irrigation water stored in the root zone to the average depth of irrigation water applied.

$$AE = \frac{\text{Average depth of water stored in root zone}}{\text{Average depth of water applied}}$$

AE gives no indication of the adequacy of the irrigation, and with underirrigation it can equal 100 percent. AE merely shows the fraction of applied water stored within the root zone that is potentially accessible for evaporation and transpiration.

Design Efficiency (DE). The ratio of planned depth or irrigation, usually equal to management allowed deficiency (MAD), in a large part of the area, usually 70 to 100 percent, to the average depth of water applied. The design efficiency can be expressed:

$$DE = \frac{\text{Planned depth of irrigation equal to MAD in j part of the area}}{\text{Average depth applied}}$$

$DE_{(j)}$ is used for system design. For example, a $DE_{80} = 75\%$ implies that 80 percent of the area should receive at least 75 percent of the average depth of application. It is not always economical or advisable to use a design efficiency that would result in having 100 percent of the area fully irrigated. There is always a certain amount of nonuniformity of distribution in any system. To fully irrigate the very driest part of the area may require excessive irrigations elsewhere.

Distribution Uniformity (DU). The ratio of the minimum depth of irrigation water infiltrated to the average depth of the irrigation water infiltrated.

$$DU = \frac{\text{Minimum depth of water infiltrated}}{\text{Average depth of water infiltrated}}$$

The minimum depth can be determined as the average of the lowest one-fourth of measured values of water stored, where each measured value represents an equal area. DU is a useful indicator of distribution problems. A low DU indicates that deep percolation losses are excessive if adequate irrigation is supplied to all areas.

Irrigation Efficiency (IE). The ratio of the average depth of irrigation water that is used beneficially to the average depth of irrigation water applied.

$$IE = \frac{\text{Average depth of water used beneficially}}{\text{Average depth of water applied}}$$

IE is a general term, useful for describing the effectiveness of irrigation on a single field, especially if irrigation is used for other than satisfying SWD, i.e., used for salt leaching, frost protection, crop cooling, pesticide, or fertilizer applications. For multiple fields, IE can be used to take into account the beneficial reuse of runoff, deep percolation, and other return flows.

Management Allowed Deficit (MAD). The desired soil moisture deficit at the time of irrigation. It can be expressed as the percentage of available soil water capacity or as the depth of water that has been depleted from the root zone. In arid areas, the ideal irrigation is generally scheduled to just cancel MAD if no leaching is required. In humid areas, ideal supplemental irrigations are often scheduled only to partly cancel MAD, i.e., to leave some root-zone capacity for the storage of anticipated rainfall.

Soil Water Deficit (SWD). The difference between field capacity and the actual moisture in the soil root zone at any given time. It is the amount of water required to bring the soil in the root zone to field capacity.

Other Irrigation Terms

Advance Time (T_t). The time it takes water to advance from the upper end to a selected station along the furrow, frequently called travel time.

Alternate-Row Irrigation. The practice of applying water to every other furrow and then, at the next irrigation, applying a similar amount of water only to the alternate furrows.

Application Rate. The rate at which water is applied to a given area. Usually expressed in inches of depth per hour or in gallons per minute.

Application Time (T_i). The amount of time that water is applied to an irrigation set.

Cumulative Intake. The depth of water absorbed by a soil from the time of initial water application to a specified elapsed time.

Deep Percolation Loss. The water that penetrates below the root-zone depth. The depth of root zone is generally the depth from which the crop is currently capable of extracting soil water. However, it may also be expressed as the depth from which the crop can extract water when mature or the depth from which a crop to be planted in the future can extract soil water.

Effective Precipitation (PE). That part of the total precipitation that is not lost to runoff, deep percolation, or evaporation before the crop can use it.

Evapotranspiration (ET) (Consumptive use). The sum of the transpiration and evaporation from an area coverd by vegetation. It is composed of four factors: evaporation from water surfaces, soil-water evaporation, evaporation from the surface of plants, and transpiration.

Every-Other-Row Irrigation (Skip row). The practice of applying water to every other furrow and applying water to the same furrows every irrigation throughout the cropping season.

Final Intake Rate. The rate at which the soil absorbs water when the infiltration velocity has become nearly constant.

Gated Pipe. A portable pipe with small gates installed along one side for distributing water to corrugations or furrows.

Head. The height of water surface above any plane or reference expressed in units of length.

Hydraulic Radius. The cross-sectional area of a stream or conduit divided by the length of the periphery that is in contact with the water.

Initial Intake. The depth of water absorbed by a soil during the period of rapid or comparatively rapid intake following the initial application.

Initial Intake Rate. The average rate at which water is absorbed by a soil during the period of rapid or comparatively rapid intake following the initial application of water.

Intake Opportunity Time. The amount of time water is infiltrating at any given point along an irrigated corrugation or furrow.

Moisture Replacement Depth. The depth of soil to be brought to field capacity.

Permeability (as used in describing soils). The readiness with which water penetrates or passes through soil pores.

Recession Curve. The descending part of a stream flow or the time lapse after water application has stopped until the water recedes or disappears from the surface at selected stations along the furrow.

Runoff Loss. The irrigation water that leaves the field as surface flow. Irrigation runoff can be returned for beneficial use by a tailwater recovery and return flow system.

Saturate. To fill all the voids between soil particles with irrigation water.

Soil Density. The mass per unit-bulk volume of soil that has been dried to constant weight at 150°C.

Soil Sealing. The orientation and packing of dispersed soil particles in the intermediate surface layer of soil so that it becomes almost impermeable to water.

Surface Soil. The upper part of the soil ordinarily moved in tillage, about 4 to 8 inches in thickness.

Soil Water Terms

The following terms are used to describe soil-water status or the soil's water-holding characteristics. The definitions are admittedly simplified descriptions of the actual physical conditions. Such simplification is necessary for practical use of the concepts. For precise use, the method of measurement or estimation should be stated along with the numerical value of

each term. The term soil moisture is assumed to be synonymous with the term soil water. Soil-water units can be expressed as percentages of dry weight of soil, percentages of volume of soil, or equivalent surface depth of water per unit depth of soil. Generally, depth of water per depth of soil in the root zone is the most convenient measurement for irrigation evaluation and management.

Available Soil Water Capacity (AWC). The water that can be held in the soil's root zone between field capacity and wilting point.

Available Soil Water (ASW). The difference at any given time between the actual water content in the soil's root zone and the wilting point.

Field Capacity (FC). Water remaining in a soil following wetting and natural drainage until free drainage has practically ceased. The time required for cessation of free drainage varies with soil texture and structure and the rate of water use by crops.

Limited Irrigation. An irrigation that replaces less than SWD in the total depth and/or area of the entire root zone. High frequency limited irrigation may permit maximum yield if the evapotranspiration requirements of the crop are met.

Wilting Point (WP). The water content in the soil's root zone at which plants can no longer extract water at a sufficient rate for survival.

Appendix—Programmable Calculator Programs for Texas Instruments Model 59

Graded Furrow Design

The program computes inflow time (T_i), efficiency (E), runoff (RO), and deep percolation (DP) for selected values of intake family (I_f), furrow spacing (W), design application depth (F_x = da), slope (S), inflow rate (Q), and furrow length (L).

User's Instructions:

Step	*Procedure*	*Enter*	*Press*		*Display*
1	Enter card, or place	1			1
	in LRN mode and key	2			2
	in program				
2	Enter data Intake family	I_f'	2nd	A′	
	Furrow spacing, ft	W	2nd	B′	
	Design applic., in.	F_x=da		A	
	Furrow slope, ft/ft	S		B	
	Inflow rate, gpm	Q		C	
	Furrow length, ft	L		D	
3	Initiate program			E	
	Inflow time, min.				T_i
	Efficiency, %			R/S	E
	Runoff, in.			R/S	RO
	Deep perc. in.			R/S	DP

Program Limits:

1. Maximum efficiency less than 100%.
2. Average intake (F_{ave}) must be less than total inflow depth (F_i).

Program Listing

000	91	R/S	051	03	03	101	43	RCL
001	76	LBL	052	34	$\sqrt{X}$	102	01	01
002	16	A′	053	54	)	103	65	X
003	42	STO	054	45	Y^x	104	05	5
004	01	01	055	93	.	105	93	.
005	91	R/S	056	04	4	106	08	8
006	76	LBL	057	02	2	107	06	6
007	11	A	058	04	4	108	05	5
008	42	STO	059	07	7	109	03	3
009	02	02	060	54	)	110	85	+
010	91	R/S	061	54	)	111	02	2
011	76	LBL	062	85	+	112	03	3
012	12	B	063	93	.	113	93	.
013	42	STO	064	07	7	114	02	2
014	03	03	065	04	4	115	01	1
015	91	R/S	066	06	6	116	01	1
016	76	LBL	067	02	2	117	54	)
017	13	C	068	54	)	118	42	STO
018	42	STO	069	55	÷	119	08	08
019	04	04	070	43	RCL	120	53	(
020	91	R/S	071	23	23	121	53	(
021	76	LBL	072	54	)	122	53	(
022	14	D	073	42	STO	123	43	RCL
023	42	STO	074	06	06	124	01	01
024	05	05	075	53	(	125	85	+
025	91	R/S	076	43	RCL	126	93	.
026	76	LBL	077	01	01	127	01	1
027	17	B′	078	65	x	128	06	6
028	42	STO	079	93	.	129	06	6
029	23	23	080	00	0	130	02	2
030	91	R/S	081	00	0	131	08	8
031	76	LBL	082	01	1	132	01	1
032	15	E	083	05	5	133	54	)
033	53	(	084	07	7	134	55	÷
034	53	(	085	06	6	135	04	4
035	53	(	086	04	4	136	07	7
036	93	.	087	85	+	137	93	.
037	02	2	088	93	.	138	04	4
038	06	6	089	00	0	139	06	6
039	08	8	090	00	0	140	07	7
040	06	6	091	00	0	141	09	9
041	65	X	092	04	4	142	00	0
042	53	(	093	04	4	143	04	4
043	43	RCL	094	06	6	144	54	)
044	04	04	095	08	8	145	45	Y^x
045	65	x	096	05	5	146	93	.
046	93	.	097	54	)	147	07	7
047	00	0	098	42	STO	148	01	1
048	04	4	099	07	07	149	06	6
049	55	÷	100	53	(	150	03	3
050	43	RCL						

Program Listing (cont.)

151	07	7	201	01	01	251	65	x
152	08	8	202	75	—	252	43	RCL
153	54	)	203	93	.	253	05	05
154	42	STO	204	06	6	254	54	)
155	09	09	205	03	3	255	42	STO
156	01	1	206	09	9	256	12	12
157	32	XIT	207	07	7	257	22	INV
158	43	RCL	208	03	3	258	23	LNX
159	01	01	209	07	7	259	42	STO
160	77	GE	210	54	)	260	13	13
161	19	D′	211	55	÷	261	53	(
162	53	(	212	03	3	262	43	RCL
163	53	(	213	03	3	263	05	05
164	53	(	214	03	3	264	65	x
165	43	RCL	215	00	0	265	43	RCL
166	01	01	216	04	4	266	13	13
167	75	—	217	93	.	267	55	÷
168	93	.	218	06	6	268	43	RCL
169	00	0	219	07	7	269	08	08
170	02	2	220	02	2	270	54	)
171	54	)	221	09	9	271	42	STO
172	55	÷	222	02	2	272	14	14
173	03	3	223	54	)	273	53	(
174	03	3	224	45	Y^x	274	53	(
175	93	.	225	93	.	275	53	(
176	03	3	226	00	0	276	43	RCL
177	06	6	227	02	2	277	02	02
178	04	4	228	01	1	278	55	÷
179	05	5	229	01	1	279	43	RCL
180	07	7	230	07	7	280	06	06
181	03	3	231	01	1	281	54	)
182	54	)	232	54	)	282	75	—
183	45	Y^x	233	42	STO	283	93	.
184	93	.	234	10	10	284	02	2
185	00	0	235	76	LBL	285	07	7
186	06	6	236	34	$\sqrt{X}$	286	05	5
187	08	8	237	53	(	287	54	)
188	06	6	238	53	(	288	55	÷
189	02	2	239	43	RCL	289	43	RCL
190	54	)	240	07	07	290	09	09
191	42	STO	241	55	÷	291	54	)
192	10	10	242	43	RCL	292	45	Y^x
193	61	GTO	243	04	04	293	43	RCL
194	34	$\sqrt{X}$	244	55	÷	294	10	10
195	76	LBL	245	43	RCL	295	35	1/X
196	19	D′	246	03	03	296	54	)
197	53	(	247	34	$\sqrt{X}$	297	42	STO
198	53	(	248	54	)	298	15	15
199	53	(	249	42	STO	299	85	+
200	43	RCL	250	11	11	300	43	RCL

Program Listing (cont.)

301	14	14
302	54	)
303	42	STO
304	16	16
305	91	R/S
306	53	(
307	53	(
308	53	(
309	53	(
310	43	RCL
311	13	13
312	65	x
313	53	(
314	43	RCL
315	12	12
316	75	—
317	01	1
318	54	)
319	54	)
320	85	+
321	01	1
322	54	)
323	55	÷
324	43	RCL
325	08	08
326	55	÷
327	43	RCL
328	05	05
329	55	÷
330	43	RCL
331	11	11
332	33	X^2
333	54	)
334	94	+/-
335	85	+
336	43	RCL
337	16	16
338	54	)
339	42	STO
340	17	17
341	53	(
342	53	(
343	53	(
344	43	RCL
345	17	17
346	45	Y^x
347	43	RCL
348	10	10
349	54	)
350	65	x
351	43	RCL
352	09	09
353	85	+
354	93	.
355	02	2
356	07	7
357	05	5
358	54	)
359	65	X
360	43	RCL
361	06	06
362	54	)
363	42	STO
364	18	18
365	53	(
366	01	1
367	93	.
368	06	6
369	00	0
370	04	4
371	01	1
372	65	x
373	43	RCL
374	04	04
375	65	x
376	43	RCL
377	16	16
378	55	÷
379	43	RCL
380	05	05
381	55	÷
382	43	RCL
383	23	23
384	54	)
385	42	STO
386	19	19
387	35	1/X
388	65	x
389	43	RCL
390	02	02
391	65	x
392	01	1
393	00	0
394	00	0
395	54	)
396	42	STO
397	20	20
398	01	1
399	00	0
400	00	0
401	32	XIT
402	43	RCL
403	20	20
404	77	GE
405	18	C′
406	43	RCL
407	20	20
408	91	R/S
409	53	(
410	43	RCL
411	19	19
412	75	—
413	43	RCL
414	18	18
415	54	)
416	42	STO
417	21	21
418	91	R/S
419	53	(
420	43	RCL
421	18	18
422	75	—
423	43	RCL
424	02	02
425	54	)
426	42	STO
427	22	22
428	91	R/S
429	92	RTN
430	76	LBL
431	18	C′
432	81	RST
433	92	RTN
434	00	0

Labels Used

002	16	A′
007	11	A
012	12	B
017	13	C
022	14	D
027	17	B′
032	15	E
196	19	D′
236	34	$\sqrt{X}$
431	18	C′

Sample Problem:

Input

0.5	I_f'
2.5	W, ft
3.	F_x, in.
0.001	S, ft/ft
10.00	Q, gpm
1000.00	L, ft.

Output

2361.066087	T_i, min.
19.80257608	E, %
6.510412807	RO, in.
5.639131312	DP, in.

Register Contents

	No.	
0.	00	
0.5	01	I_f'
3.	02	F_x
0.001	03	S
10.	04	Q
1000.	05	L
.6141336954	06	P/w
0.00123505	07	d
26.14365	08	c
.0470691052	09	a
.7474788656	10	b
0.003905571	11	$d/QS^{1/2}$
3.905571024	12	$dL/QS^{1/2}$
49.67843941	13	$e^{dL/QS^{1/2}}$
1900.210545	14	T_T
460.8554922	15	T_n
2361.066037	16	T_i
1996.595433	17	T_o
8.639131312	18	F_{ave}
15.14954412	19	F_i
19.80257608	20	E
6.510412807	21	RO
5.639131312	22	DP
2.5	23	W

Level Furrow Design

The program computes advance (T_t), inflow time (T_i), deep percolation (DP), and application efficiency (E). This program can also be used for computing plotting points for level furrow design charts. Use of a printer is optional.

User's Instructions:

Step	*Procedure*	*Enter*	*Press*	*Display*
1	Partition Registers	3	2nd OP 17	719.29
2	Enter cards or place	1		1.
	in LRN mode and key	2		2.
	in program	3		3.
3	Enter Data			
	Furrow intake family	I_f	2nd A′	I_f*
	Furrow spacing, ft	W	2nd B′	W*
	Inflow rate, gpm	Q	A	Q*
	Length, ft	L	B	L*
	Design application, in	F_n	C	F_n*
4a	Initiate program w/o printer Inflow			
	time, min		E	T_i
	Advance time, min		R/S	T_t
	Deep percolation, in		R/S	DP
	Application efficiency,%		R/S	E
4b	Initiate program w/printer Inflow			
	time, min		E	T_i*
	Advance time, min			T_t*
	Deep percolation, in			DP*
	Application efficiency,%			E*
5	Repeat for different values			

*Printed by printer

Any one or all input values may be changed for another solution.

Program Limits:

Error display will occur when:

1. Inflow rate is greater than 60 gpm.
   a. Without printer blinking 60 (decrease Q).
   b. With printer—"DECREASE Q-60."
2. Furrow width, W, is exceeded.
   a. Without printer blinking excess Q (decrease Q).
   b. With printer—"DECREASE Q—excess Q value printed."
3. Inflow time is greater than 3000 min.
   a. Without printer blinking T_i value shown. This will usually be a very large number (increase Q).
   b. With printer "INCREASE Q—Large T_i number printed."
4. T_t/T_n (ratio advance time to net opportunity time) greater than or equal to 5.
   a. Without printer blinking 3737 (increase Q).
   b. With printer "INCREASE Q—TT."

Program Listing

000	98	ADV	051	42	STO	101	93	.
001	61	GTO	052	15	15	102	02	2
002	98	ADV	053	00	0	103	01	1
003	91	R/S	054	02	2	104	01	1
004	76	LBL	055	07	7	105	95	=
005	16	A′	056	00	0	106	42	STO
006	42	STO	057	00	0	107	20	20
007	10	10	058	69	OP	108	43	RCL
008	02	2	059	04	04	109	10	10
009	04	4	060	43	RCL	110	65	x
010	02	2	061	15	15	111	93	.
011	01	1	062	69	DP	112	00	0
012	69	OP	063	06	06	113	00	0
013	04	04	064	91	R/S	114	01	1
014	43	RCL	065	76	LBL	115	05	5
015	10	10	066	13	C	116	07	7
016	69	OP	067	42	STO	117	06	6
017	06	06	068	16	16	118	04	4
018	81	R/S	069	02	2	119	85	+
019	76	LBL	070	01	1	120	93	.
020	17	B′	071	03	3	121	00	0
021	42	STO	072	01	1	122	00	0
022	12	12	073	69	OP	123	00	0
023	04	4	074	04	04	124	04	4
024	03	3	075	43	RCL	125	04	4
025	00	0	076	16	16	126	06	6
026	00	0	077	69	OP	127	08	8
027	69	OP	078	06	06	128	05	5
028	04	04	079	91	R/S	129	95	=
029	43	RCL	080	76	LBL	130	42	STO
030	12	12	081	15	E	131	21	21
031	69	OP	082	02	2	132	43	RCL
032	06	06	083	00	0	133	13	13
033	91	R/S	084	69	OP	134	45	Y^x
034	76	LBL	085	07	07	135	93	.
035	11	A	086	69	OP	136	03	3
036	42	STO	087	19	19	137	04	4
037	13	13	088	25	CLR	138	01	1
038	03	3	089	43	RCL	139	09	9
039	04	4	090	10	10	140	65	x
040	00	0	091	65	x	141	93	.
041	00	0	092	05	5	142	01	1
042	69	OP	093	93	.	143	01	1
043	04	04	094	08	8	144	01	1
044	43	RCL	095	06	6	145	06	6
045	13	13	096	05	5	146	55	÷
046	69	OP	097	03	3	147	43	RCL
047	06	06	098	85	+	148	15	15
048	91	R/S	099	02	2	149	95	=
049	76	LBL	100	03	3	150	42	STO
050	12	B						

Program Listing (cont.)

151	11	11	201	08	8	251	22	INV
152	06	6	202	06	6	252	53	(
153	01	1	203	95	=	253	53	(
154	32	XIT	204	85	+	254	43	RCL
155	43	RCL	205	93	.	255	10	10
156	13	13	206	07	7	256	75	—
157	77	GE	207	04	4	257	93	.
158	34	$\sqrt{X}$	208	06	6	258	00	0
159	43	RCL	209	02	2	259	02	2
160	12	12	210	95	=	260	54	)
161	75	—	211	42	STO	261	55	÷
162	93	.	212	22	22	262	03	3
163	03	3	213	43	RCL	263	03	3
164	04	4	214	10	10	264	93	.
165	05	5	215	85	+	265	03	3
166	95	=	216	93	.	266	06	6
167	55	÷	217	01	1	267	04	4
168	93	.	218	06	6	268	05	5
169	00	0	219	02	2	269	07	7
170	02	2	220	02	2	270	03	3
171	02	2	221	08	8	271	54	)
172	95	=	222	01	1	272	45	Y^x
173	42	STO	223	95	=	273	93	.
174	24	24	224	55	÷	274	00	0
175	32	XIT	225	04	4	275	06	6
176	43	RCL	226	07	7	276	08	8
177	13	13	227	93	.	277	06	6
178	77	GE	228	04	4	278	02	2
179	23	LNX	229	06	6	279	95	=
180	43	RCL	230	07	7	280	42	STO
181	13	13	231	09	9	281	19	19
182	65	x	232	00	0	282	61	GTO
183	93	.	233	04	4	283	43	RCL
184	00	0	234	95	=	284	76	LBL
185	04	4	235	45	Y^x	285	22	INV
186	55	÷	236	93	.	286	53	(
187	43	RCL	237	07	7	287	53	(
188	11	11	238	01	1	288	43	RCL
189	34	$\sqrt{X}$	239	06	6	289	10	10
190	95	=	240	03	3	290	75	—
191	45	Y^x	241	07	7	291	93	.
192	93	.	242	08	8	292	06	6
193	04	4	243	95	=	293	03	3
194	02	2	244	42	STO	294	09	9
195	04	4	245	18	18	295	07	7
196	07	7	246	01	1	296	03	3
197	65	x	247	32	XIT	297	07	7
198	93	.	248	43	RCL	298	54	)
199	02	2	249	10	10	299	55	÷
200	06	6	250	77	GE	300	03	3

Program Listing (cont.)

301	03	3	351	07	07	401	95	=
302	03	3	352	43	RCL	402	55	÷
303	00	0	353	15	15	403	43	RCL
304	04	4	354	55	÷	404	18	18
305	93	.	355	43	RCL	405	95	=
306	06	6	356	20	20	406	45	Y^x
307	07	7	357	55	÷	407	43	RCL
308	02	2	358	43	RCL	408	19	19
309	09	9	359	14	14	409	35	1/X
310	02	2	360	33	x^2	410	95	=
311	54	)	361	95	=	411	42	STO
312	45	Y^x	362	65	x	412	09	09
313	93	.	363	53	(	413	85	+
314	00	0	364	53	(	414	43	RCL
315	02	2	365	43	RCL	415	08	08
316	01	1	366	14	14	416	95	=
317	01	1	367	75	—	417	45	Y^x
318	07	7	368	01	1	418	43	RCL
319	01	1	369	54	)	419	19	19
320	95	=	370	65	x	420	65	x
321	42	STO	371	53	(	421	43	RCL
322	19	19	372	43	RCL	422	18	18
323	76	LBL	373	14	14	423	95	=
324	43	RCL	374	54	)	424	85	+
325	43	RCL	375	22	INV	425	93	.
326	21	21	376	23	LNX	426	02	2
327	55	÷	377	85	+	427	07	7
328	43	RCL	378	01	1	428	05	5
329	13	13	379	54	)	429	95	=
330	55	—	380	95	=	430	65	x
331	43	RCL	381	94	+/-	431	43	RCL
332	11	11	382	85	+	432	22	22
333	34	$\sqrt{X}$	383	43	RCL	433	65	x
334	95	=	384	07	07	434	43	RCL
335	65	x	385	95	=	435	15	15
336	43	RCL	386	42	STO	436	55	÷
337	15	15	387	08	08	437	01	1
338	95	=	388	43	RCL	438	93	.
339	42	STO	389	16	16	439	06	6
340	14	14	390	65	x	440	00	0
341	22	INV	391	43	RCL	441	04	4
342	23	LNX	392	12	12	442	01	1
343	65	x	393	55	÷	443	55	÷
344	43	RCL	394	43	RCL	444	43	RCL
345	15	15	395	22	22	445	13	13
346	55	÷	396	75	—	446	95	=
347	43	RCL	397	93	.	447	42	STO
348	20	20	398	02	2	448	17	17
349	95	=	399	07	7	449	03	3
350	42	STO	400	05	5	450	00	0

Program Listing (cont.)

451	00	0	501	16	16	551	17	17
452	01	1	502	65	X	552	69	OP
453	32	XIT	503	01	1	553	06	06
454	43	RCL	504	00	0	554	03	3
455	17	17	505	00	0	555	07	7
456	77	GE	506	95	=	556	03	3
457	35	1/X	507	75	—	557	07	7
458	05	5	508	43	RCL	558	69	OP
459	32	XIT	509	16	16	559	04	04
460	43	RCL	510	95	=	560	43	RCL
461	07	07	511	42	STO	561	07	07
462	55	÷	512	05	05	562	69	OP
463	43	RCL	513	87	IFF	563	06	06
464	09	09	514	07	07	564	01	1
465	95	=	515	24	CE	565	06	6
466	77	GE	516	58	FIX	566	03	3
467	50	IxI	517	00	00	567	03	3
468	43	RCL	518	43	RCL	568	69	OP
469	17	17	519	17	17	569	04	04
470	65	x	520	91	R/S	570	58	FIX
471	43	RCL	521	43	RCL	571	02	02
472	13	13	522	07	07	572	43	RCL
473	65	x	523	91	R/S	573	05	05
474	01	1	524	58	FIX	574	69	OP
475	93	.	525	02	02	575	06	06
476	06	6	526	43	RCL	576	01	1
477	00	0	527	05	05	577	07	7
478	04	4	528	91	R/S	578	02	2
479	01	1	529	43	RCL	579	01	1
480	95	=	530	06	06	580	02	2
481	35	1/X	531	58	FIX	581	01	1
482	65	x	532	01	01	582	69	OP
483	43	RCL	533	56	DEL	583	04	04
484	15	15	534	22	INV	584	43	RCL
485	65	x	535	52	EE	585	06	06
486	43	RCL	536	22	INV	586	58	FIX
487	12	12	537	58	FIX	587	01	01
488	65	x	538	91	R/S	588	52	EE
489	43	RCL	539	76	LBL	589	22	INV
490	16	16	540	24	CE	590	52	EE
491	65	x	541	98	ADV	591	22	INV
492	01	1	542	58	FIX	592	58	FIX
493	00	0	543	00	00	593	69	OP
494	00	0	544	03	3	594	06	06
495	95	=	545	07	7	595	98	ADV
496	42	STO	546	02	2	596	91	R/S
497	06	06	547	04	4	597	76	LBL
498	35	1/X	548	69	DP	598	34	$\sqrt{X}$
499	65	x	549	04	04	599	86	STF
500	43	RCL	550	43	RCL	600	01	01

Program Listing (cont.)

601	61	GTO
602	45	Y^x
603	76	LBL
604	23	LNX
605	86	STF
606	02	02
607	76	LBL
608	45	Y^x
609	69	OP
610	00	00
611	03	3
612	05	5
613	01	1
614	07	7
615	01	1
616	06	6
617	04	4
618	01	1
619	01	1
620	05	5
621	69	OP
622	02	02
623	01	1
624	07	7
625	00	0
626	00	0
627	03	3
628	04	4
629	00	0
630	00	0
631	00	0
632	00	0
633	69	OP
634	03	03
635	69	OP
636	05	05
637	87	IFF
638	01	01
639	39	COS
640	87	IFF
641	02	02
642	30	TAN
643	76	LBL
644	39	COS
645	06	6
646	00	0
647	99	PRT
648	81	RST
649	76	LBL
650	30	TAN
651	43	RCL
652	24	24
653	99	PRT
654	81	RST
655	76	LBL
656	35	1/X
657	86	STF
658	00	00
659	76	LBL
660	50	IxI
661	69	OP
662	00	00
663	02	2
664	04	4
665	03	3
666	01	1
667	01	1
668	05	5
669	03	3
670	05	5
671	01	1
672	07	7
673	69	OP
674	02	02
675	01	1
676	03	3
677	03	3
678	06	6
679	01	1
680	07	7
681	00	0
682	00	0
683	03	3
684	04	4
685	69	OP
686	03	03
687	69	OP
688	05	05
689	87	IFF
690	00	00
691	44	SUM
692	69	OP
693	00	00
694	03	3
695	07	7
696	03	3
697	07	7
698	69	OP
699	02	02
700	69	OP
701	05	05
702	81	RST
703	76	LBL
704	44	SUM
705	03	3
706	07	7
707	02	2
708	04	4
709	69	OP
710	04	04
711	43	RCL
712	17	17
713	69	OP
714	06	06
715	81	RST
716	00	0
717	00	0
718	00	0
719	00	0

Labels Used

005	16	A′
020	17	B′
035	11	A
050	12	B
066	13	C
081	15	E
285	22	INV
324	43	RCL
540	24	CE
598	34	$\sqrt{X}$
604	23	LNX
608	45	Y^x
644	39	COS
650	30	TAN
656	35	1/X
660	50	IxI
704	44	SUM

Sample Problem:

Sample Problem (with printer)

2.	IF	Input Data
2.5	W	
5.	Q	
600.	L	
3.	FN	
INCREASE Q		Error Condition, $T_i > 3000$
3.199639 10	TI	
10.	Q	
INCREASE Q		Error Condition, $T_i > 3000$
358954.039	TI	
20.	Q	
INCREASE Q		Error Condition, $T_t/T_n \geq 5$
TT		
30.	Q	
INCREASE Q		Error Condition, $T_t/T_n \geq 5$
TT		
40.	Q	
149.	TI	Output data
141.	TT	
3.39	DP	
47.	EFF	

Try a Q of 70 gpm as a sample.

70.	Q
REDUCE Q	Error Condition, $Q > 60$
60.	

Sample Problem (w/o printer)

2.	I_f	Input Data
2.5	W	
5.	Q	
600.	L	
3.	F_n	
2450791353.		Error Condition, (blinking value) shows that T_i>3000 minutes
10.	Q	Try 10 gpm
52683.33062		Error Condition, (blinking value) shows that T_i>3000 minutes
20.	Q	Try 20 gpm
3737.		Error Condition, (blinking value) the number 3737 indicates that T_t is too great
30.	Q	Try 30 gpm
3737.		Error Condition, (blinking value) the number 3737 indicates that T_t is too great
40.	Q	Try 40 gpm
102.	T_i	Output Data
141.	T_t	
1.37	DP	
68.6	E	

Try a Q of 70 gpm as a sample

70.	Q	Try 70 gpm
60.		Error Condition, (blinking 60) Q > 60

Sample Problem:

Register Content

		Register
0.		00
0.		01
0.		02
0.		03
0.		04
3.38630671	DP	05
46.8755077	E	06
141.2504802	T_t	07
102.1624894	T_{adv}	08
59.94169168	T_n	09
2.	I_f	10
.0007949722	s	11
2.5	W	12
60.	Q	13
2.107283211	$d/QS^{1/2}$	14
600.	L	15
3.	F_n	16
149.2964913	T_i	17
.1095374361	a	18
.8073892693	b	19
34.9416	c	20
0.00359965	d	21
2.300916425	p	22
0.		23
97.95454545	$Qmas^2$	24
0.		25
0.		26
0.		27
0.		28
0.		29

Cutback Furrow Design

The program computes total inflow time (T_i), time at which the inflow rate is reduced to one-half (T_t), surface runoff (RO), deep percolation (DP), and application efficiency (E). The program can also be used for computing plotting points for cutback furrow design charts. Use of a printer is optional.

User's Instructions:

Step	*Procedure*	*Enter*	*Press*	*Display*
1	Partition Registers	3	2nd OP 17	719.29
2	Enter cards or place in	1		1.
	LRN mode and key program	2		2.
		3		3.
3	Enter data			
	Furrow intake family	I_f	2nd A′	I_f*
	Furrow slope, ft/ft	S	2nd B′	S*
	Furrow spacing, ft	W	2nd C′	W*
	Inflow rate, gpm	Q	A	Q*
	Length, ft	L	B	L*
	Design application, in	F_n	C	F_n*
4a	Initiate program w/o printer Inflow			
	time, min		E	T_i
	Advance (cutoff) time, min		R/S	T_t
	Runoff, in		R/S	RO
	Deep percolation, in		R/S	DP
	Application efficiency,%		R/S	E
4b	Initiate program w/printer			
	Inflow time, min		E	T_i*
	Advance (cutoff) time, min			T_t*
	Runoff, in			RO*
	Deep percolation, in			DP*
	Application efficiency,%			E*
5	Repeat for different input values Any one or all input values may be changed for another solution.			

*Printed by printer

Program Limits:

Inflow rate is limited to 50 gpm. Error display will occur when inflow time is greater than 3000 min:

1. Without printer blinking T_i value shown. Increase Q or reduce length.
2. With printer increase Q and large T_i number printed. Increase Q, or reduce length.

Program Listing

000	98	ADV	051	42	STO	101	69	OP
001	61	GTO	052	13	13	102	19	19
002	98	ADV	053	03	3	103	25	CLR
003	91	R/S	054	04	4	104	43	RCL
004	76	LBL	055	00	0	105	10	10
005	16	A·	056	00	0	106	65	x
006	42	STO	057	69	OP	107	05	5
007	10	10	058	04	04	108	93	.
008	02	2	059	43	RCL	109	08	8
009	04	4	060	13	13	110	06	6
010	02	2	061	69	OP	111	05	5
011	01	1	062	06	06	112	03	3
012	69	OP	063	91	R/S	113	85	+
013	04	04	064	76	LBL	114	02	2
014	43	RCL	065	12	B	115	03	3
015	10	10	066	42	STO	116	93	.
016	69	OP	067	15	15	117	02	2
017	06	06	068	00	0	118	01	1
018	91	R/S	069	02	2	119	01	1
019	76	LBL	070	07	7	120	95	=
020	17	B′	071	00	0	121	42	STO
021	42	STO	072	00	0	122	20	20
022	11	11	073	69	OP	123	43	RCL
023	03	3	074	04	04	124	10	10
024	06	6	075	43	RCL	125	65	x
025	00	0	076	15	15	126	93	.
026	00	0	077	69	DP	127	00	0
027	69	OP	078	06	06	128	00	0
028	04	04	079	91	R/S	129	01	1
029	43	RCL	080	76	LBL	130	05	5
030	11	11	081	13	C	131	07	7
031	69	OP	082	42	STO	132	06	6
032	06	06	083	16	16	133	04	4
033	91	R/S	084	02	2	134	85	+
034	76	LBL	085	01	1	135	93	.
035	18	C′	086	03	3	136	00	0
036	42	STO	087	01	1	137	00	0
037	12	12	088	69	OP	138	00	0
038	04	4	089	04	04	139	04	4
039	03	3	090	43	RCL	140	04	4
040	00	0	091	16	16	141	06	6
041	00	0	092	69	OP	142	08	8
042	69	OP	093	06	06	143	05	5
043	04	04	094	91	R/S	144	95	=
044	43	RCL	095	76	LBL	145	42	STO
045	12	12	096	15	E	146	21	21
046	69	DP	097	02	2	147	53	(
047	06	06	098	00	0	148	43	RCL
048	91	R/S	099	69	OP	149	13	13
049	76	LBL	100	07	07	150	65	x
050	11	A						

Program Listing (cont.)

151	93	.
152	00	0
153	04	4
154	55	÷
155	43	RCL
156	11	11
157	34	$\sqrt{X}$
158	54	)
159	45	Y^x
160	93	.
161	04	4
162	02	2
163	04	4
164	07	7
165	65	x
166	93	.
167	02	2
168	06	6
169	08	8
170	06	6
171	95	=
172	85	+
173	93	.
174	07	7
175	04	4
176	06	6
177	02	2
178	95	=
179	55	÷
180	43	RCL
181	12	12
182	95	=
183	42	STO
184	22	22
185	53	(
186	43	RCL
187	13	13
188	65	x
189	93	.
190	05	5
191	65	x
192	93	.
193	00	0
194	04	4
195	55	÷
196	43	RCL
197	11	11
198	34	$\sqrt{X}$
199	54	)
200	45	Y^x
201	93	.
202	04	4
203	02	2
204	04	4
205	07	7
206	65	x
207	93	.
208	02	2
209	06	6
210	08	8
211	06	6
212	95	=
213	85	+
214	93	.
215	07	7
216	04	4
217	06	6
218	02	2
219	95	=
220	55	÷
221	43	RCL
222	12	12
223	95	=
224	42	STO
225	28	28
226	43	RCL
227	10	10
228	85	+
229	93	.
230	01	1
231	06	6
232	06	6
233	02	2
234	08	8
235	01	1
236	95	=
237	55	÷
238	04	4
239	07	7
240	93	.
241	04	4
242	06	6
243	09	9
244	00	0
245	04	4
246	95	=
247	45	Y^x
248	93	.
249	07	7
250	01	1
251	06	6
252	03	3
253	07	7
254	08	8
255	95	=
256	42	STO
257	18	18
258	01	1
259	32	XIT
260	43	RCL
261	10	10
262	77	GE
263	22	INV
264	53	(
265	53	(
266	43	RCL
267	10	10
268	75	—
269	93	.
270	00	0
271	02	2
272	54	)
273	55	÷
274	03	3
275	03	3
276	93	.
277	03	3
278	06	6
279	04	4
280	05	5
281	07	7
282	03	3
283	54	)
284	45	Y^x
285	93	.
286	00	0
287	06	6
288	08	8
289	06	6
290	02	2
291	95	=
292	42	STO
293	19	19
294	61	GTO
295	43	RCL
296	76	LBL
297	22	INV
298	53	(
299	53	(
300	43	RCL

Program Listing (cont.)

301	10	10	351	29	29	401	00	0
302	75	—	352	65	x	402	01	1
303	93	.	353	43	RCL	403	32	XIT
304	06	6	354	15	15	404	43	RCL
305	03	3	355	54	)	405	14	14
306	09	9	356	22	INV	406	77	GE
307	07	7	357	23	LNX	407	35	1/X
308	03	3	358	65	x	408	53	(
309	07	7	359	43	RCL	409	43	RCL
310	54	)	360	15	15	410	20	20
311	55	—	361	55	÷	411	65	x
312	03	3	362	43	RCL	412	43	RCL
313	03	3	363	20	20	413	15	15
314	03	3	364	95	=	414	65	x
315	00	0	365	42	STO	415	43	RCL
316	04	4	366	07	07	416	29	29
317	93	.	367	53	(	417	33	X^2
318	06	6	368	53	(	418	54	)
319	07	7	369	53	(	419	35	1/X
320	02	2	370	43	RCL	420	65	x
321	09	9	371	16	16	421	53	(
322	02	2	372	65	x	422	53	(
323	54	)	373	43	RCL	423	43	RCL
324	45	Y^x	374	28	28	424	29	29
325	93	.	375	35	1/X	425	65	x
326	00	0	376	75	—	426	43	RCL
327	02	2	377	93	.	427	15	15
328	01	1	378	02	2	428	75	—
329	01	1	379	07	7	429	01	1
330	07	7	380	05	5	430	54	)
331	01	1	381	54	)	431	65	x
332	95	=	382	55	÷	432	53	(
333	42	STO	383	43	RCL	433	43	RCL
334	19	19	384	18	18	434	29	29
335	76	LBL	385	54	)	435	65	x
336	43	RCL	386	45	Y^x	436	43	RCL
337	53	(	387	43	RCL	437	15	15
338	43	RCL	388	19	19	438	54	)
339	21	21	389	35	1/X	439	22	INV
340	55	÷	390	54	)	440	23	LNX
341	53	(	391	42	STO	441	85	+
342	43	RCL	392	09	09	442	01	1
343	13	13	393	85	+	443	54	)
344	65	x	394	43	RCL	444	54	)
345	43	RCL	395	07	07	445	42	STO
346	11	11	396	95	=	446	08	08
347	34	$\sqrt{X}$	397	42	STO	447	01	1
348	54	)	398	14	14	448	93	.
349	54	)	399	03	3	449	06	6
350	42	STO	400	00	0	450	00	0

Program Listing (cont.)

451	04	4	501	05	5	551	16	16
452	01	1	502	95	=	552	54	)
453	65	x	503	65	x	553	42	STO
454	53	(	504	43	RCL	554	23	23
455	53	(	505	28	28	555	53	(
456	43	RCL	506	95	=	556	43	RCL
457	13	13	507	42	STO	557	16	16
458	65	x	508	06	06	558	55	÷
459	43	RCL	509	43	RCL	559	43	RCL
460	07	07	510	08	08	560	24	24
461	54	)	511	45	Y^x	561	65	x
462	85	+	512	43	RCL	562	01	1
463	53	(	513	19	19	563	00	0
464	43	RCL	514	65	x	564	00	0
465	13	13	515	43	RCL	565	54	)
466	65	x	516	18	18	566	42	STO
467	93	.	517	95	=	567	25	25
468	05	5	518	85	+	568	87	IFF
469	65	x	519	93	.	569	07	07
470	43	RCL	520	02	2	570	24	CE
471	09	09	521	07	7	571	58	FIX
472	54	)	522	05	5	572	00	00
473	54	)	523	95	=	573	43	RCL
474	55	÷	524	65	x	574	14	14
475	43	RCL	525	53	(	575	91	R/S
476	12	12	526	43	RCL	576	43	RCL
477	55	÷	527	22	22	577	07	07
478	43	RCL	528	75	—	578	91	R/S
479	15	15	529	43	RCL	579	58	FIX
480	95	=	530	28	28	580	02	02
481	42	STO	531	54	)	581	43	RCL
482	24	24	532	95	=	582	17	17
483	53	(	533	85	+	583	91	R/S
484	43	RCL	534	43	RCL	584	43	RCL
485	14	14	535	06	06	585	23	23
486	75	—	536	95	=	586	91	R/S
487	43	RCL	537	42	STO	587	43	RCL
488	08	08	538	06	06	588	25	25
489	54	)	539	94	+/-	589	58	FIX
490	45	Y^x	540	85	+	590	01	01
491	43	RCL	541	43	RCL	591	52	EE
492	19	19	542	24	24	592	22	INV
493	65	x	543	95	=	593	52	EE
494	43	RCL	544	42	STO	594	22	INV
495	18	18	545	17	17	595	58	FIX
496	95	=	546	53	(	596	91	R/S
497	85	+	547	43	RCL	597	76	LBL
498	93	.	548	06	06	598	24	CE
499	02	2	549	75	—	599	98	ADV
500	07	7	550	43	RCL	600	58	FIX

Program Listing (cont.)

601	00	00
602	03	3
603	07	7
604	02	2
605	04	4
606	69	OP
607	04	4
608	43	RCL
609	14	14
610	69	OP
611	06	06
612	03	3
613	07	7
614	03	3
615	07	7
616	69	OP
617	04	04
618	43	RCL
619	07	07
620	69	OP
621	06	06
622	03	3
623	05	5
624	03	3
625	02	2
626	69	OP
627	04	04
628	58	FIX
629	02	02
630	43	RCL
631	17	17
632	69	OP
633	06	06
634	01	1
635	06	6
636	03	3
637	03	3
638	69	OP
639	04	04
640	43	RCL
641	23	23
642	69	OP
643	06	06
644	01	1
645	07	7
646	02	2
647	01	1
648	02	2
649	01	1
650	69	OP
651	04	04
652	43	RCL
653	25	25
654	58	FIX
655	01	01
656	52	EE
657	22	INV
658	52	EE
659	22	INV
660	58	FIX
661	69	OP
662	06	06
663	98	ADV
664	91	R/S
665	81	RST
666	76	LBL
667	35	1/X
668	86	STF
669	00	00
670	76	LBL
671	50	IxI
672	69	OP
673	00	00
674	02	2
675	04	4
676	03	3
677	01	1
678	01	1
679	05	5
680	03	3
681	05	5
682	01	1
683	07	7
684	69	OP
685	02	02
686	01	1
687	03	3
688	03	3
689	06	6
690	01	1
691	07	7
692	00	0
693	00	0
694	03	3
695	04	4
696	69	OP
697	03	03
698	69	OP
699	05	05
700	03	3
701	07	7
702	02	2
703	04	4
704	69	OP
705	04	04
706	43	RCL
707	14	14
708	69	OP
709	06	06
710	81	RST
711	00	0
712	00	0

Labels Used

005	16	A′
020	17	B′
035	18	C′
050	11	A
065	12	B
081	13	C
096	15	E
297	22	INV
336	43	RCL
598	24	CE
667	35	1/X
678	50	IxI

Sample Problem

Sample Problem (with printer)

Input	0.3	IF
	0.004	S
	2.5	W
	10.	Q
	900.	L
	3.	FN
Output	1344.	TI
	133.	TT
	2.07	RO
	0.20	DP
	57.	EFF

Register Content

0.		00
0.		01
0.		02
0.		03
0.		04
0.		05
3.221026651	F_{ave}	06
133.426623	T_t	07
88.3318671	To	08
1210.134647	Tnc	09
0.3	I_f	10
0.004	S	11
2.5	W	12
10.	Q	13
1343.56127	T_i	14
900.	L	15
3.	Fn	16
2.043942858	RO	17
.0364487762	a	18
.7203376724	b	19
24.97059	c	20
0.00091977	d	21
5336399931	P/W	22
.2210266506	DP	23
5.264969508	Fg	24
56.98038698	E	25
45.09475593		26
0.		27
.4736726975	P_1/W	28
.0014542841	$d/QS^{1/2}$	29

1.	IF	Input	
0.002	S		
2.5	W		
10.	Q		
1200.	L		
3.	FN		
INCREASE Q		Error	
9676.736769	TI	T_i>3000	
15.	Q	Try Q=15 gpm	
1785.	TI	Output	
1540.	TT		
0.99	RO		
9.35	DP		
22.5	EFF		
30.	Q	Try Q=30 gpm	
455.	TI	Output	
252.	TT		
0.61	RO		
2.06	DP		
52.9	EFF		

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Section 15

IRRIGATION

Chapter 6

CONTOUR-LEVEE IRRIGATION

Soil Conservation Service
United States Department of Agriculture

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 6--CONTOUR-LEVEE IRRIGATION

CONTENTS

	Page
Application principles	6-1
Adaptability	6-1
Crops	6-1
Soils	6-1
Topography	6-2
Climate	6-2
Advantages	6-3
Limitations in use	6-3
Land preparation requirements	6-4
Detailed investigations	6-7
Soils	6-7
Topography	6-7
Water supply	6-7
Layout of levee systems	6-7
Levee dimensions	6-8
Irrigation stream sizes	6-9
Delivery systems	6-13
Application systems	6-14
Drainage requirements	6-17
Operation	6-17
Crops other than rice	6-17
Operation for rice	6-18
Water use efficiency	6-19
Sample design problems	6-19

FIGURES

Figure		Page
6-1	Accumulated intake for irrigation by the contour-levee method	6-2
6-2a	Typical topography of a 40-acre field to be irrigated by the contour-levee method showing levees and drains if land were not smoothed or leveled	6-5

Figure		Page
6-2b	Same field showing contour levees after land smoothing	6-5
6-2c	Same field after constructing parallel levees and leveling basins	6-6
6-2d	Same field after constructing uniform basins	6-6
6-3	Accumulated intake vs. time for example soil	6-10
6-4	Engineering plan for sample contour-levee irrigation system	6-15
6-5	Cross sections--sample contour-levee irrigation system	6-16
6-6	Drainage coefficient curves for Southwest	6-24

NOMENCLATURE

A = Area irrigated in acres

E = Field application efficiency in percent

F_g = Gross depth of application in inches

F_n = Net depth of application in inches

f = Time allowed for one complete irrigation in days

h = Daily system operation time in hours

Q = Required irrigation stream in cubic feet per second

q = Required stream size per acre in acre-inches per hour or cubic feet per second per acre

T_n = Time required for the net depth of application (F_n) to infiltrate the soil in minutes

u = Peak-period consumptive-use rate in inches per day

vi = Vertical interval between levees in feet or inches

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 6--CONTOUR-LEVEE IRRIGATION

Application Principles

In irrigating by the contour-levee method water is applied to nearly level strips or areas of predetermined size at a rate enough in excess of the intake rate of the soil to permit rapid coverage. Water is retained by small dikes or levees that surround the strips and are constructed longitudinally on the contour. In rice irrigation, each strip is covered with water to a depth that controls weed growth without damaging the rice. This is known as flooding. Water is continuously added to replace water lost through evapotranspiration, deep percolation, and boundary levees. This is called maintaining the flood. For other crops water is kept on the strips until the desired depth has entered the soil. The excess water is then drained off by gravity and used on a similar strip at a lower elevation. This step is called flushing and is repeated often enough to meet water requirements of the crop.

Adaptability

Crops

The contour-levee method has been used for many years for flooding rice fields. It has been adapted to the irrigation of pasture grasses, hay crops, small grains, and some row crops. Row crops irrigated by this method are those that can stand temporary flooding or flushing without damage, namely, cotton, corn, and soybeans. This method is not recommended for irrigating vegetables, tobacco, and other row crops easily damaged by temporary flooding.

Soils

Contour-levee irrigation is adapted to medium- to fine-textured soils having an available water holding capacity of no less than 1.25 inches per foot of depth nor less than 2.5 inches for the root zone depth of the crop being irrigated.

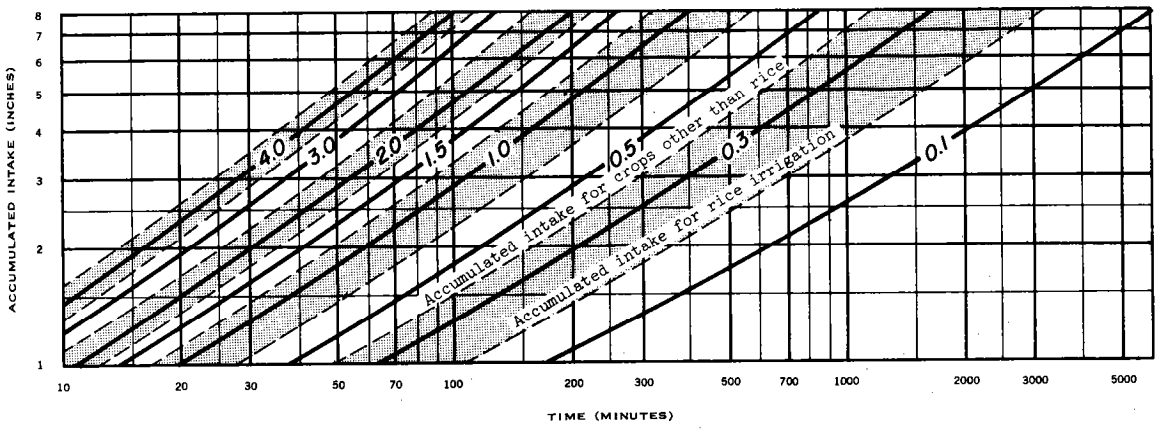


Figure 6-1.--Accumulated intake for irrigation by the contour-levee method.

Soil intake rates for the desired net depth of application should not exceed those upper limits shown in figure 6-1. For example, if a 3-inch application were planned for cotton, the intake opportunity time should not be less than 300 minutes. Intake rates for contour-levee irrigation are shown in local irrigation guides where they are known. Otherwise, they are measured by the cylinder-infiltrometer method.

Because of the difficulty of maintaining the flood on soils planted to rice, they should contain a restrictive layer with a permeability rate of 0.02 inch per hour or less.

Topography

For this method, best results are obtained where slopes do not exceed 0.5 percent. Greater slopes, however, can be reduced by land leveling. Where leveling is required, the soil must be deep enough to permit leveling without undue loss of productivity.

If contour levees are used for irrigating row crops, the slope in the direction of row drainage becomes a limiting factor. The maximum practical slope is that which will not result in erosion from storm runoff. In areas where this method is now being used, slope ranges from 0.05 to 0.3 percent depending on erodibility of the soil. The minimum slope is that which will provide adequate drainage, usually 0.05 to 0.15 percent. Slopes must be within these limits or must be obtainable at reasonable cost by landing leveling.

Climate

The contour-levee method can be used successfully for irrigating rice and close-growing crops in any climate to which these crops are adapted, provided the prerequisites regarding soil and topography can be met. Levees are usually temporary for row crops and are usually not built

until the crop needs to be irrigated for the first time so that they will not interfere with operation of the cultivating equipment. In humid areas where this method is common for irrigating row crops, rainfall usually is adequate during the early growing season and irrigation is not required until cultivation has been completed. When cultivation becomes necessary after an irrigation, the levees are plowed down by the cultivating equipment. They are then rebuilt to make maximum use of subsequent rainfall. In areas where insufficient rainfall during the early growing season would require frequent reconstruction of levees, the contour-levee method is not recommended for irrigating row crops.

Advantages

The contour-levee method has several advantages.

(1) It permits the irrigation of low-intake-rate soils that are difficult to irrigate by other methods.
(2) Maximum utilization of rainfall reduces seasonal irrigation requirements.
(3) Uniform distribution of water and high field-application efficiency are easily obtained.
(4) Since the same system removes excess storm runoff, adequate drainage can be provided at little extra expense. This is very important in areas of high rainfall.
(5) Installation costs depend largely on the amount of land preparation required. Where the unit volume of leveling is moderate, installation costs are low compared with most other methods.
(6) Simple, easily operated controls permit handling large irrigation streams with minimum labor. One irrigator can usually handle up to 300 acres including pump attendance.

Limitations in Use

Some limitations and disadvantages of the method are:

(1) It is restricted to irrigating crops that can stand temporary flooding for 12 hours or more without damage.
(2) It cannot be used successfully on soils having moderate to rapid intake characteristics (fig. 6-1).
(3) Some degree of land leveling is usually required.
(4) Large irrigation streams are required.
(5) Light net applications are difficult to make efficiently.
(6) Levees, ditches, and structures need frequent maintenance.

Land Preparation Requirements

Contour levees require some land preparation. Figures 6-2a, b, c, d illustrate the different degrees to which a typical 40-acre field can be prepared for this method of irrigation. Though these illustrations were prepared for irrigating rice, they are adaptable to the irrigation of field and forage crops.

Without land preparation, long levees, ditches, and canals may be required; water cannot be applied uniformly or efficiently; water management is difficult; and production costs, especially for labor, are high. Figure 6-2a shows the topography of a field before land preparation. It also shows the extent of levees and drains if levees were constructed at a vertical interval of 0.2 foot on the original topography.

Eliminating minor surface irregularities improves the topography of the field. Smoothing, usually with a land plane, permits laying out a usable irrigation and drainage system, but levees, ditches, and canals are still too long and basins are irregular in shape and variable in size, making efficient irrigation difficult (fig. 6-2b).

For more efficient operation of planting, cultivating, and harvesting equipment and for better water management, the levees should be parallel and the basins of uniform width (fig. 6-2c). The levees can be staked parallel on approximate contours first and each basin then leveled to a uniform plane, or the entire field can be leveled first and the levees then staked parallel and on the contour. This results in increased water-use efficiency, high crop yields, and reduced production costs.

An additional refinement that further increases water-use efficiency and facilitates water management consists of dividing the field into units or basins of equal size and shape by levees that are straight and parallel. The levees can be constructed first and the basins then leveled and each treated as a separate field, or the entire field can be leveled first and the levees constructed afterward. Where land is leveled by water leveling, level basins result. The slope required for drainage is obtained by plowing the basin toward the center, thus building up a ridge (fig. 6-2d).

Where conventional land leveling is used, the basins usually are sloping planes (p. 6-15). Neither type of basin is considered to have an advantage over the other.

These basins, equal in size and shape, while more expensive to construct, increase water-use efficiency and reduce labor costs.

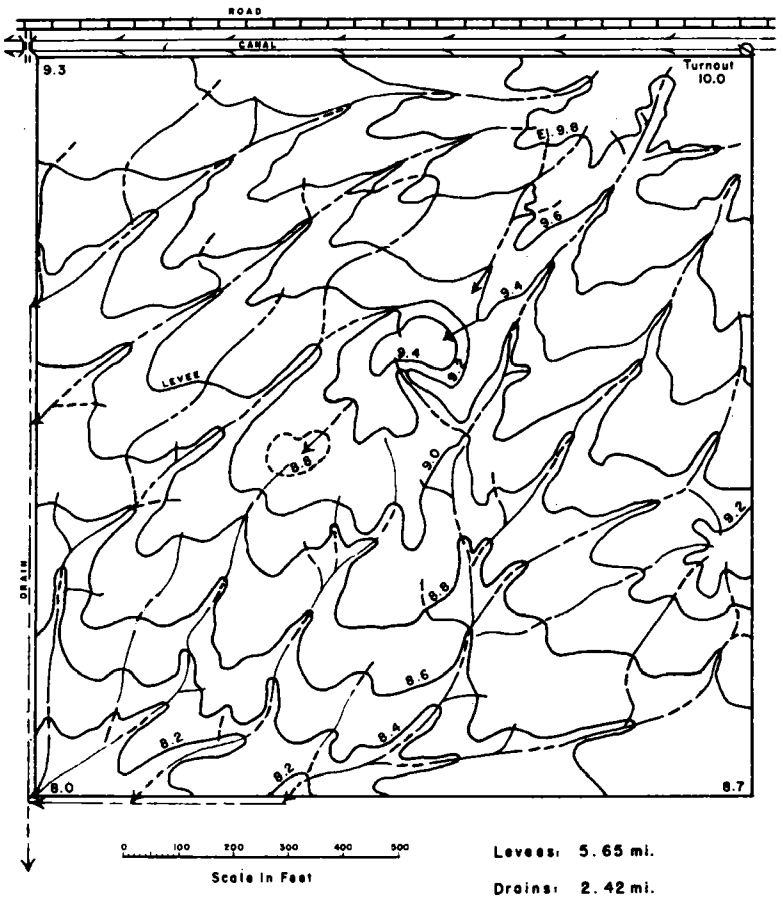


Figure 6-2a.--Typical topography of a 40-acre field to be irrigated by the contour-levee method showing levees and drains if land were not smoothed or leveled.

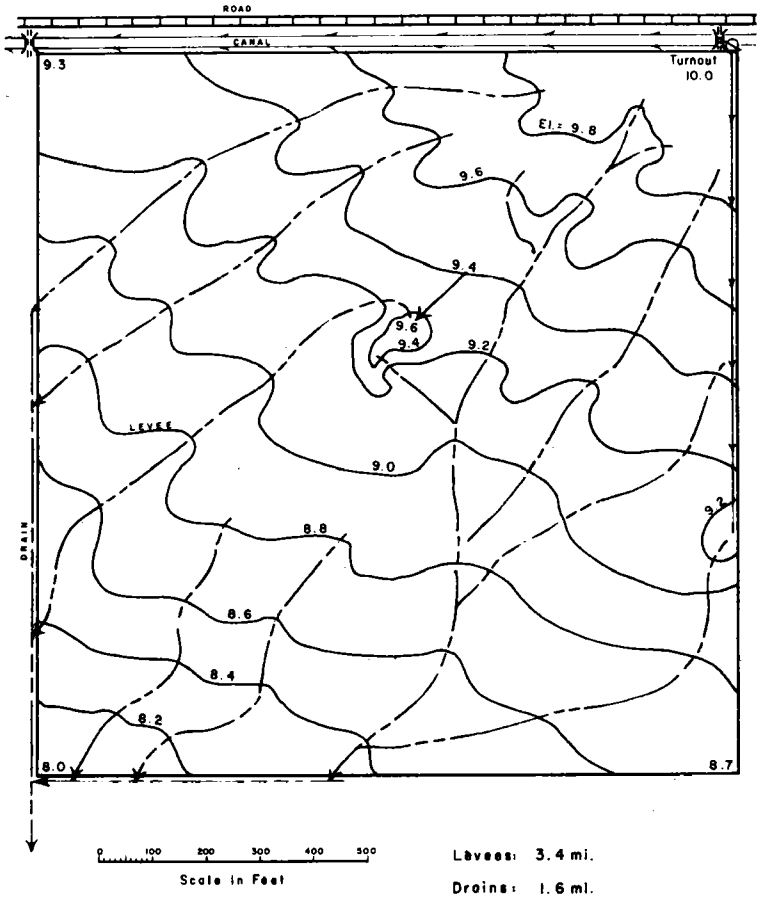


Figure 6-2b.--Same field showing contour levees after land smoothing.

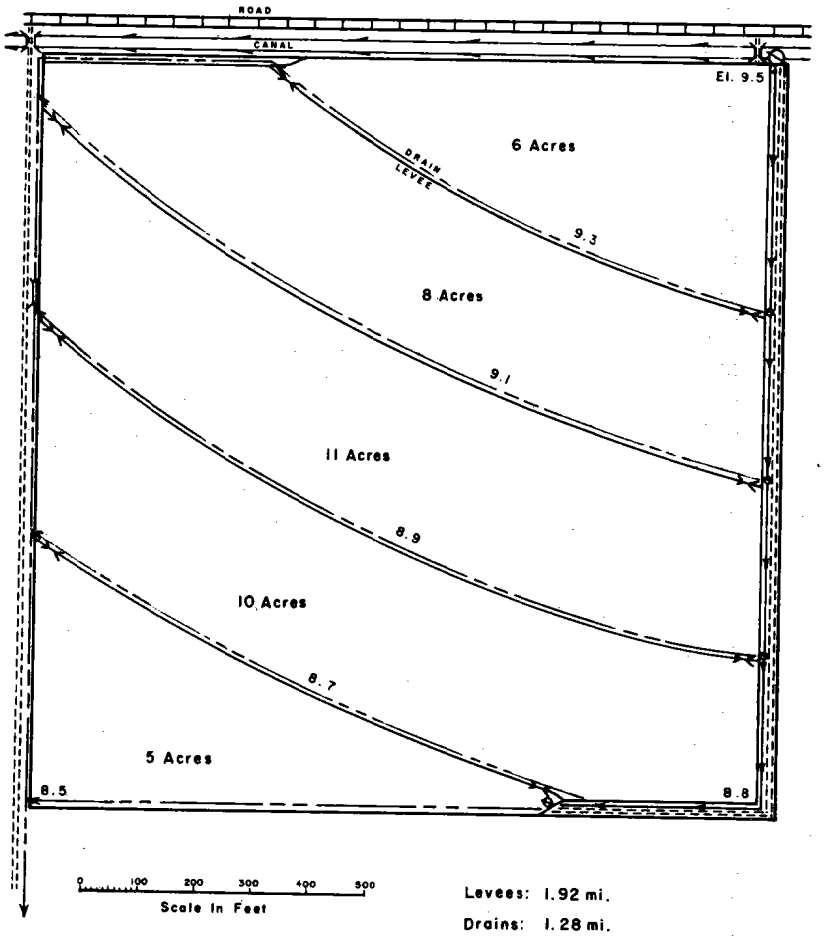


Figure 6-2c.--Same field after constructing parallel levees and leveling basins.

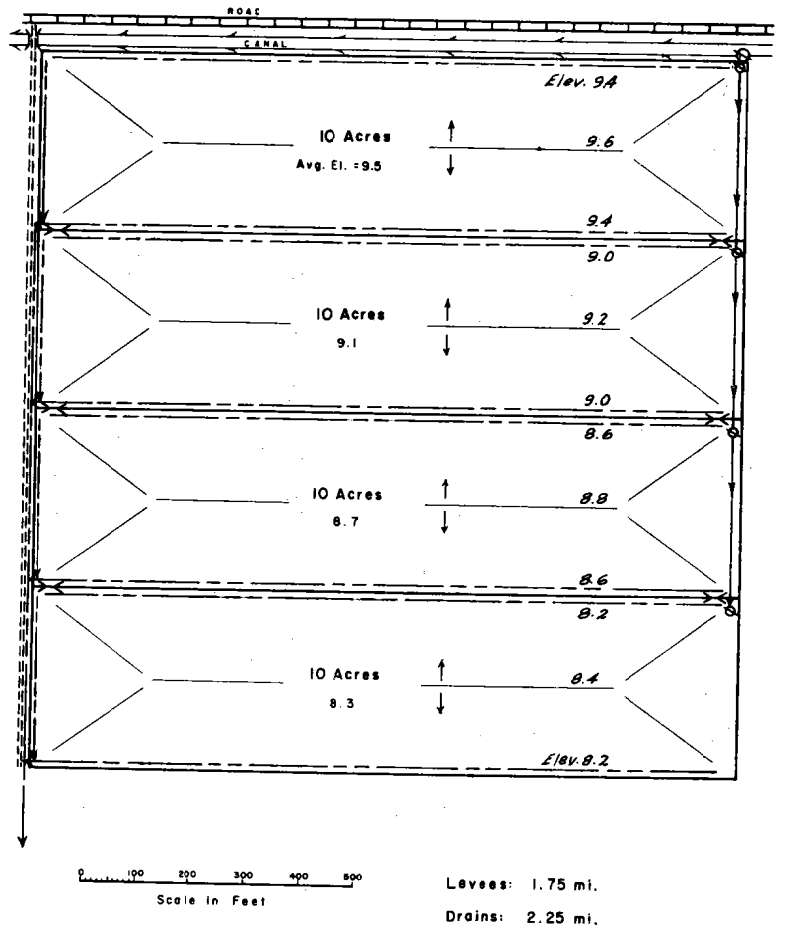


Figure 6-2d.--Same field after constructing uniform basins.

Detailed Investigations

Soils

A detailed soil map of the area to be irrigated is a prerequisite to planning a contour-levee system. The intake characteristics of each soil must be known. If they cannot be obtained from the local irrigation guide, they will have to be measured by the cylinder-infiltrometer method. For soils on which rice is to be irrigated, the permeability rate of the restricting layer must be known.

The available water holding capacity of the significant layers of each soil should be known. These are usually obtained from the local irrigation guide.

Topography

A topographic map of the area to be irrigated facilitates planning the contour-levee system. Information on the map should include, in addition to contour lines, the location and elevation of the water source and drainage outlet. The map should also show any pipelines, drains, power-lines, structures, roads, or other important physical features.

The topographic map can be based on either a conventional or grid survey. Aerial photographs may serve the purpose of a topographic map if old contour levees are visible and if they adequately describe the topography.

Water Supply

Dependable stream sizes available for irrigation should be measured or estimated. The available stream sizes determine the number of acres of a given crop that can be irrigated (p. 6-9).

The quality of the water with respect to its intended use should be determined.

Layout of Levee Systems

If an adequate contour map is available, the levee system can be laid out on the map before making the layout on the ground. This saves time and effort in the field.

The first step is to determine the maximum-size unit or basin that can be irrigated with the stream size available (sample calculations 3 and 4).

The shape of the basins is important. To prevent overtopping of the levees, the dimension of any basin in the direction of the prevailing wind should not exceed about 400 feet. Length of the basin may be restricted by drainage requirements. The channel above the levee along the lower

side of a basin removes both excess irrigation water and storm runoff. Thus this length should be limited to that which permits the channel to provide such removal in a reasonable length of time. Basins draining in one direction should not be longer than 660 feet. Where the basin has more than one drainage outlet, its length may be increased.

The levees must be laid out on the contour or so located that they will be on the contour after land preparation. If practicable they should be laid out parallel to each other. To facilitate planting, tillage, and harvesting levees should be straight or gently curving.

The ideal vertical interval between levees is about 0.2 to 0.4 foot. Smaller vertical intervals can be used on very flat land to reduce the size of the unit areas to that compatible with the available irrigation stream. Somewhat larger vertical intervals may be used in small parts of a field to maintain a minimum horizontal interval of about 40 feet. Larger vertical intervals, however, require higher levees, usually resulting in a decrease in water-use efficiency.

The levees should provide basins of nearly equal size. This makes irrigation easier and increases water-use efficiency. After the contour levees are located, the basins are closed by constructing end levees. A typical layout of a contour-levee system is shown on page 6-15.

Locate roadways to provide access to each basin by farm machinery (p. 6-15). These roadways are of particular importance if harvesting has to be done in wet weather. Culverts or bridges must be provided at each ditch crossing.

Levee Dimensions

The settled height of the levees must equal the sum of the vertical interval between levees, the depth of water to be applied, and a freeboard of at least 3 inches (0.25 foot) for protection against wave action. For noncompacted levees at least 0.3 foot more should be added for settlement. The constructed height of a typical levee is computed as follows:

Vertical interval between levees	0.2 foot
Depth of water to be applied (3.6 in.).....	.3 foot
Freeboard.....	.3 foot
Settlement allowance.....	.3 foot
Constructed height.....	1.1 feet

Where levees are torn down and rebuilt to facilitate planting and tillage of row crops, side slopes should be no steeper than 1-1/2 horizontal to 1 vertical. Where they are permanent as in pastures, side slopes should be no steeper than 3 or 4 to 1 to facilitate the use of mowing machinery and to minimize damage by the trampling of livestock.

A drainage channel no less than 0.5 foot deep with side slopes no steeper than 1-1/2 horizontal to 1 vertical is provided along the upper side of each levee. The material removed from the drainage channel is used to build the levee (p. 6-15). Temporary levees are usually built with border plows or border disks and wider, more permanent levees with blade graders.

Irrigation Stream Sizes

The minimum-size irrigation stream for all adapted crops other than rice must equal or exceed the greater of the following: (1) A stream large enough to satisfy peak water use requirements of the crop and to overcome deep percolation and other losses. (2) A stream large enough to permit coverage of the average-size leveed basin in a maximum of one-fourth the time required for the soil to absorb the net amount of water to be applied.

The minimum required stream that satisfies the first criterion is computed by the formula:

$$Q = \frac{A \times F_g}{f \times h}$$ See nomenclature.

To compute the minimum-size stream that satisfies the second criterion, intake characteristics of the soil (fig. 6-3), average size of the basins, and vertical interval between levees must be known.

The procedure for computing the minimum stream size is illustrated in the sample calculation which follows.

Sample calculation 1.--Determining minimum stream size for crops other than rice

Given:

An 80-acre field of cotton containing 16 basins of nearly equal size (A).....	A = 80 acres
Net depth of application (from irrigation guide).	F_n = 2.5 in.
Gross depth of application at an estimated 70 percent efficiency.....	F_g = 3.6 in.
Time allowed for one complete irrigation as agreed on with the irrigator (no greater than F_n/daily peak use rate).....	f = 8 days
Daily system operation time as agreed on with the irrigator.....	h = 12 hr
Soil intake characteristics (from cylinder-infiltration measurements).....	See figure 6-3
Average area of 16 basins in 80-acre field.....	5 acres
Vertical interval between levees.....	vi = 2.4 in.

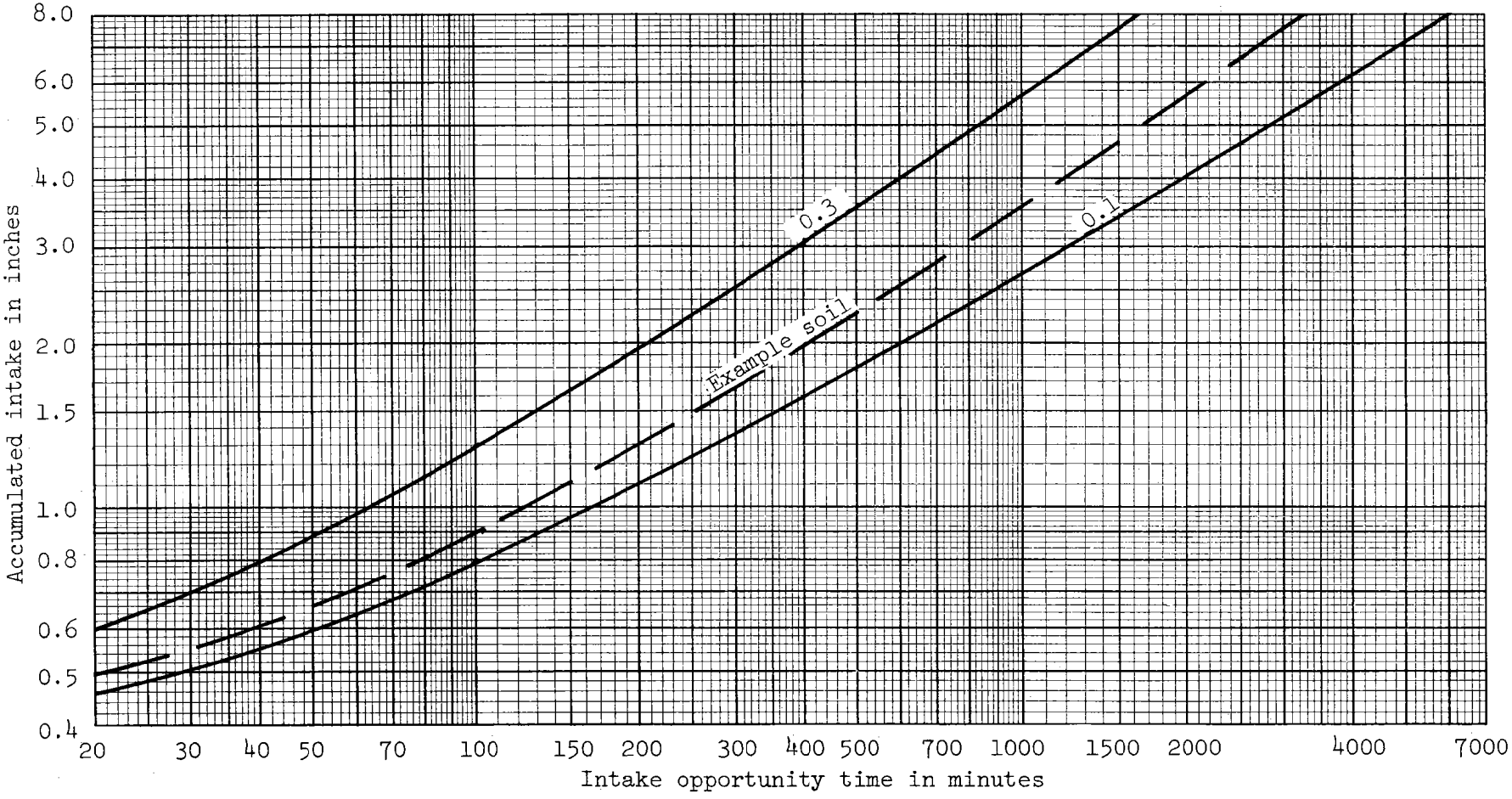


Figure 6-3.--Accumulated intake vs. time for example soil.

Find:

The minimum stream size (Q) that satisfies the two criteria.

Procedure:

Compute the minimum stream size required to satisfy the first criterion as follows:

$$Q = \frac{A \times F_g}{f \times h} = \frac{80 \text{ acre} \times 3.6 \text{ in.}}{8 \text{ days} \times 12 \text{ hr/day}} = 3.0 \text{ acre-in. per hr} = \underline{\underline{3.0}} \text{ cfs}$$

Using the example soil curve shown in figure 6-3, find the time (T_n) required for the net depth of application (F_n = 2.5 inches) to infiltrate the soil. T_n is 580 minutes.

Allowing one-fourth of the time (T_n), or 145 minutes, to cover an average-size basin, find the average depth of water that infiltrates the soil during this period. Water infiltrates the soil only along the lower side of the basin during $T_{n/4}$; there is no infiltration along the upper side. The basin is covered for 145 minutes along the lower side and for zero minutes along the upper side with an average coverage time of 72-1/2 minutes. Using figure 6-3, find the depth of water that infiltrates the soil in 72-1/2 minutes. This is 0.76 inch.

To this average depth of infiltration add the average depth of water over the basin at the end of this period. Since the vertical interval between levees is 2.4 inches, the water is that deep along the lower side of the basin and has no depth along the upper side. Thus the average depth is one-half of the vertical interval (vi) or 1.2 inches.

Compute the minimum stream size required to satisfy the second criterion as follows:

Required stream size per acre (q):

$$q = \frac{(0.76 \text{ in.} + 1.2 \text{ in.}) \times 60}{145 \text{ min}} = 0.811 \text{ acre-in. per hr} = 0.811 \text{ cfs per acre}$$

Required total stream size (Q):

$$Q = 5 \text{ acres} \times 0.811 \text{ cfs per acre} = \underline{\underline{4.06}} \text{ cfs}$$

Since the second criterion requires a greater stream size, the value 4.06 cubic feet per second is used.

In rice irrigation, there are three critical operations, any one of which may determine the required irrigation stream size: (1) Flushing, which usually follows seedbed preparation and dry planting. The irrigation stream must be large enough to cover a basin in one-fourth the time required for the soil to absorb the net amount of water applied. (2) Flooding, which is started when the plants are about 8 to 10 weeks old and are

using water at a maximum rate. The irrigation stream must be large enough to flood the entire design area to a predetermined depth--usually 3 to 4 inches--in the time required for depletion, at the peak rate, of one-half the available moisture in the root zone of the soil. (3) Maintaining the flood until about 2 weeks before harvest. The irrigation stream must be large enough to satisfy peak-period consumptive use and overcome deep percolation losses.

The procedure used for determining minimum required stream size for each of these critical operations is illustrated in the sample calculation which follows:

Sample calculation 2.--Determining minimum stream size for rice irrigation

Given:

An 80-acre field of rice containing 16 basins of nearly equal size (A).....	A = 80 acres
Available water holding capacity of soil at root zone depth (18 in.).....	= 3.6 in.
Saturated moisture capacity of soil at root zone depth.....	= 7.35 in.
Permeability of restricting layer.....	= 0.002 in/hr
Net depth of application (from irrigation guide).	F_n = 1.8 in.
Soil intake characteristics (from cylinder-infiltrometer measurements).....	See figure 6-3
Peak-period consumptive-use rate.....	u = 0.3 in/day
Vertical interval between levees.....	vi = 2.4 in.

Find:

The minimum stream size (Q) required for flushing, flooding, and maintaining the flood.

Procedure:

For flushing.--Using figure 6-3, find the time (T_n) required for the net depth of application (F_n = 1.8 inches) to infiltrate the soil. T_n is 345 minutes.

Allowing one-fourth of T_n, or 86 minutes, to cover an average-size basin (5 acres), find the average depth of water that infiltrates the soil during this period. This depth is 0.62 inch (fig. 6-3).

To this average depth of infiltration, add the average depth of water over the surface of the basin at the end of this time period. This average depth is equal to one-half the vertical distance between the levees or one-half of 2.4 inches = 1.2 inches.

Required stream size per acre (q):

$$q = \frac{(0.62 \text{ in.} + 1.20 \text{ in.})\ 60}{86 \text{ min}} = 1.27 \text{ acre-in. per hr}$$
$$= 1.27 \text{ cfs per acre}$$

Required total stream size (Q):

$$Q = 5 \text{ acres} \times 1.27 \text{ cfs per acre} = \underline{\underline{6.35}} \text{ cfs}$$

For flooding.--Find the time required for depletion of one-half the available soil moisture:

$$\frac{1/2 \times 3.6 \text{ in.}}{0.30 \text{ in. per day}} = 6 \text{ days} = 144 \text{ hr}$$

Find the depth of application to produce a 3-inch flood over the design area:

Depth of application required to saturate the soil.....	7.35 in
One-half the vertical interval between levees.....	1.20 in
Depth percolation losses (144 hr x 0.002 in. per hr)....	0.29 in.
Depth of flood.....	3.00 in.
Total application.....	11.84 in.

Then find the minimum required irrigation stream:

$$Q = \frac{80 \text{ acres} \times 11.84 \text{ in.}}{144 \text{ hr}} = 6.58 \text{ acre-in. per hr} = \underline{\underline{6.58}} \text{ cfs}$$

For maintaining the flood.--Find the minimum stream size that maintains the flood by satisfying peak consumptive use and replacing the amount lost by deep percolation:

$$Q = 80 \text{ acres} \left(\frac{0.30 \text{ in. per day}}{24 \text{ hr}} + .002 \text{ in. per hr}\right) = 1.16 \text{ acre-in. per hr} = \underline{\underline{1.16}} \text{ cfs}$$

Thus the required minimum irrigation stream is the 6.58 cubic feet per second required for the flooding operation.

Delivery Systems

The delivery system consists of the facilities required to convey water from the source of supply to the highest point in each field to be irrigated. The water may be conveyed above ground level in elevated field ditches or in low-pressure pipelines. These facilities also include the structures, valves, and measuring devices required to control and direct the water to the individual fields as needed and at the designed rate of flow.

Pipelines have obvious advantages over open ditches; they are buried, take no land out of cultivation, and require a minimum of maintenance. Open ditches cost less to install, but weed control and sediment removal are expensive.

The capacity of the delivery system must be equal to or greater than the sum of the minimum required irrigation stream for each field (sample calculations 1 and 2).

In the sample plan no delivery system is shown since the source of supply, a well, is located at the highest point in the field (fig. 6-4). The irrigation supply ditch along the north boundary of the field is considered a part of the application system.

Application Systems

The application system consists of the facilities required to distribute and apply water on all parts of a field. These facilities may include open ditches, pipelines, levees, turnouts, control structures, culverts, and other devices.

An irrigation head ditch or pipeline is used to convey water to the highest basin in each series. Water is turned into these upper basins through turnouts in head ditches or through valves in pipelines (fig. 6-5).

The head ditch consists of two parallel levees or dikes. The construction material may be borrowed from land-grading operations, from nearby borrow areas, or from the center area between the levees themselves. If levee material can be borrowed elsewhere economically and conveniently, center borrow ditches should not be used. Center borrow ditches must usually be larger than required for adequate capacity to obtain enough material for construction of the levees. Ditches of this type are necessarily wide and take up space that otherwise might be cultivated.

Since the system operates by gravity, water is conveyed above ground surface and a head of not less than 0.5 foot must be provided at the turnouts. The top of the levees forming the head ditch must be at least 1.5 feet above the highest part of the irrigated area. The head ditch should have stable side slopes, usually 1-1/2 horizontal to 1 vertical.

Several types of turnouts are used to introduce water into the basins. One of the most popular consists of a pipe with a gate on the upstream end. A 10-foot section of corrugated metal pipe with an inexpensive light steel gate is easy to install and has proven very satisfactory. Pipe diameter is determined by the design rate of flow and the head provided to obtain that flow. Several types of turnout that have proven satisfactory are shown in chapter 3.

Inside the irrigated area, water is usually conveyed from the head ditch or pipeline to the lower basins by V-type irrigation ditches which also serve as drainageways. The capacity of these ditches must be equal to the minimum required irrigation stream <u>or</u> to the computed drainage requirements, whichever is the greater. They should be at least 0.5 foot deeper than the V-type drains along the upper sides of the contour levees or a minimum of 1 foot.

There should be roadways between each series of basins for easy access to all parts of the field. Waste material placed between two parallel

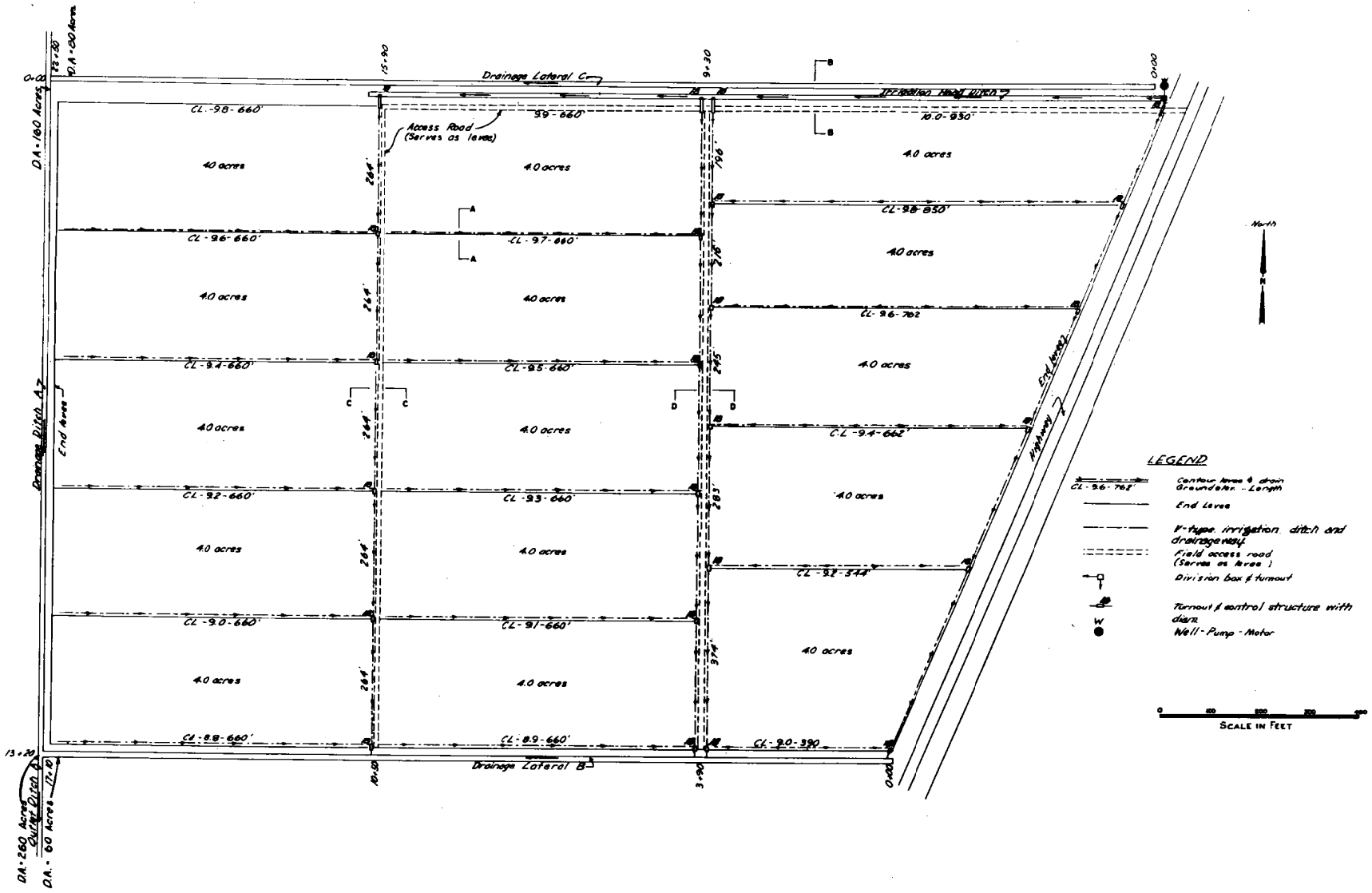
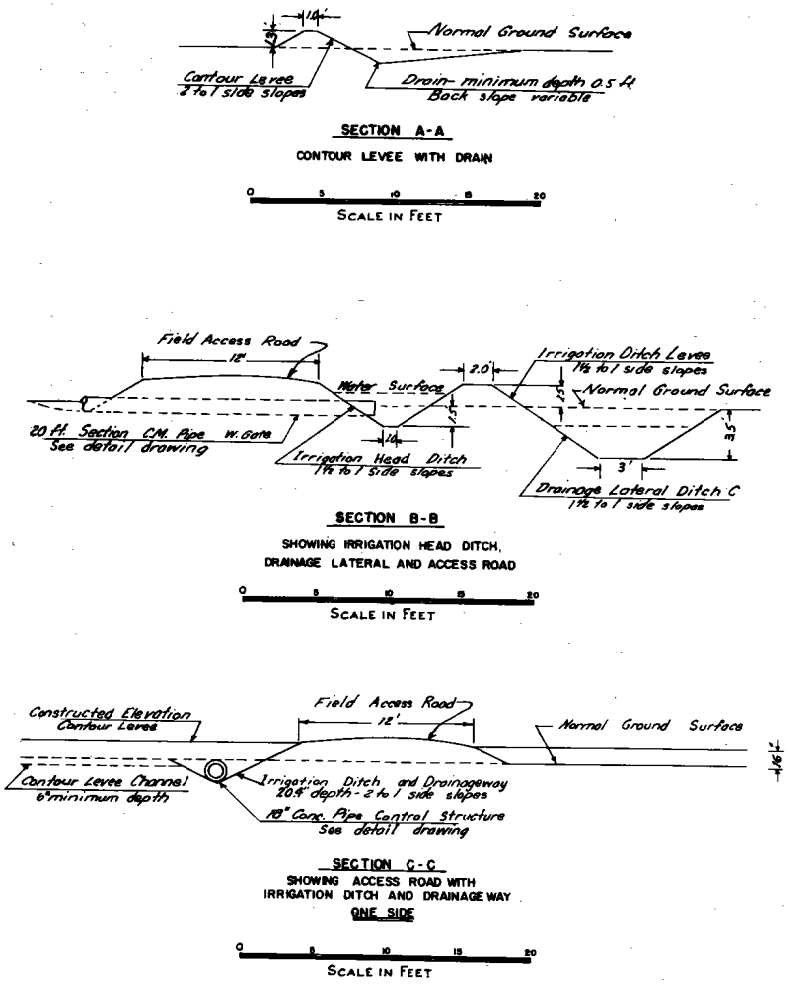


Figure 6-4.--Engineering plan for sample contour-levee irrigation system.



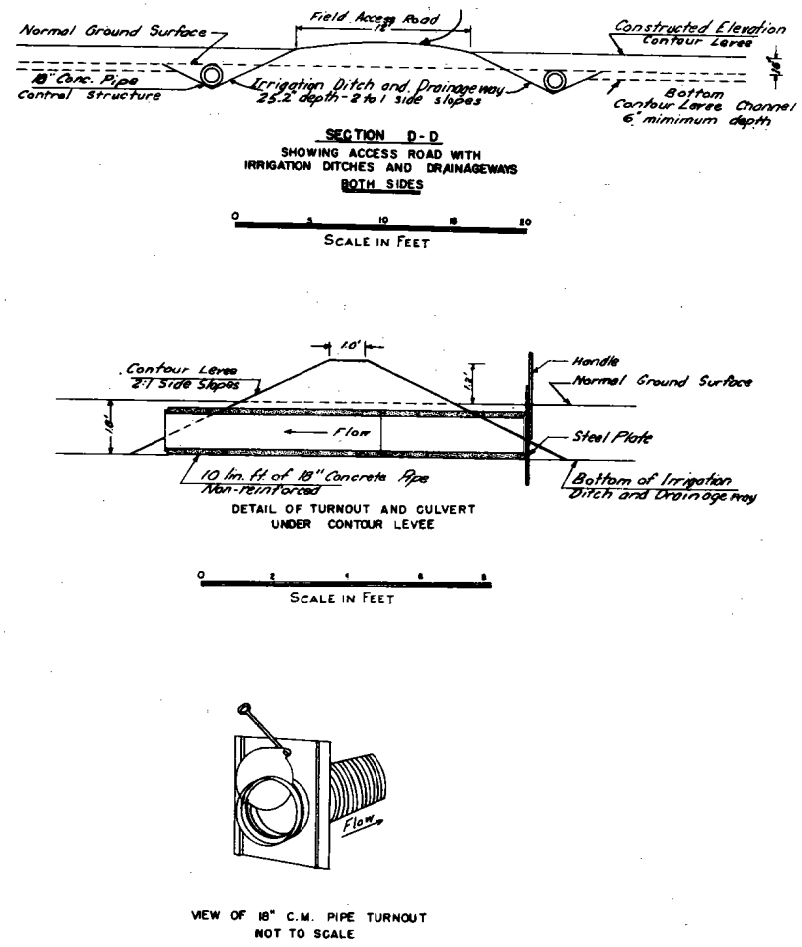


Figure 6-5.--Cross sections--sample contour-levee irrigation system.

V-type irrigation ditches can be used to form the roadway. The roadway also acts as an end levee and must be equal in height to the contour levees. Slopes should be no steeper than 1-1/2 horizontal to 1 vertical except that in pastures they should be no steeper than 3 or 4 to 1. (See section D-D, figure 6-5.)

To retain, control, and eventually remove the irrigation water suitable control structures must be placed in the irrigation ditches under each contour levee. Several types of structures have been developed. One is a concrete pipe culvert with an adjustable steel plate at its upper end (fig. 6-5). Another is a sheet metal structure that has flashboards for water control. In some levees fixed-crest weirs made of sheet metal or other suitable material are added as a further control.

The capacity of any control structure should be equal to that of the ditch in which it is placed. The structure should be designed to operate under a head not exceeding 0.5 foot. If a pipe is used, the normal diameter should be no less than 10 inches.

Drainage Requirements

The irrigation application system provides adequate drainage within the design area. Providing an adequate outlet and preventing runoff from adjacent areas entering the irrigated area are the other drainage problems.

The outlet is usually a trapezoidal channel able to provide adequate drainage for both the irrigated area and any other area it may serve. The outlet or a channel lateral to it serves the lowest basin in each series. Additional channels must be provided around the boundaries of the drainage area where needed to prevent the entrance of runoff from higher areas (fig. 6-4).

In computing the capacity of the outlet channel and its laterals provide adequate drainage for the least water-tolerant crop grown in the rotation.

Operation

The method of operation varies with the crop being irrigated and with the owner's preference for operating time. The usual methods follow.

Crops Other Than Rice

Individual basins in a series are irrigated consecutively, beginning with the highest and ending with the lowest. All control structures in the irrigation ditch serving a series of basins are closed and water from the head ditch or pipeline is then turned into the highest basin in the series. The irrigation stream discharges into the first basin

until the gross application depth plus the depth needed to cover the basin has been applied. Then the structure controlling this basin is partially opened, allowing the irrigation stream to flow into the second or next lower basin. The water flows into the second basin until the gross application has been applied. Then the third basin is flooded in similar manner. This process is continued downstream until the gross application for the series has been applied.

After water has remained on the highest basin until the desired depth has infiltrated the soil, the control structure in this basin is completely opened and the water drains off and flows onto the next lower basin. This process is continued until a complete series of basins is irrigated. This operation may be undertaken during daylight only (sample calculation 3) or may be a continuous one. Continuous operation is the more efficient since only the excess water from the last or lowest basin in a series need be drained off as waste.

Other series of basins in the field are then irrigated in like manner. When the field is not being irrigated, all control structures in the irrigation ditches are left open for drainage.

Operation for Rice

In rice irrigation, there are four operations: moisture control for germination, flooding, maintaining the flood, and removing the flood.

Moisture control for germination.--Rice is seeded either by drilling dry or by broadcasting into water from an airplane. When drilling is followed by a period of dry weather, flushing is needed to germinate the seed or to prevent loss of young seedlings through lack of moisture. The flushing process for rice is the same as for other crops.

When seeding is done from the air, the basins are flooded to a shallow depth before seeding. As soon as the rice sprouts, the water is drained off to hasten growth of the rice plants and permit them to develop deep root systems.

Flooding.--Each basin is flooded with water so as to provide weed control without damage to the rice plants. Rice is normally flooded twice during the growing season. About 3 to 4 weeks after seeding the basins are flooded to a shallow depth to control weeds and to provide adequate moisture. This flood is held on the basins for about 2 weeks after which it may be drained off and the soil surface allowed to dry out. Drying helps control root maggots, algae, and fungi. It also provides a favorable period for applying fertilizer and permits the rice straw to stiffen and resist lodging.

The second flooding comes about 7 to 9 weeks after seeding. Water requirements are high because this is during the peak consumptive-use period. Each basin is flooded to a depth of 3 inches or more and the flood is maintained for 9 to 10 weeks or from 2 to 3 weeks before harvest.

Each series of basins is flooded separately, one series being completely flooded before another is started. When the design depth of flood has been reached on the first basin, the water is turned into the next lower basin and the process repeated downstream until all basins in a series are flooded. The design depth of flood is maintained in each basin by using sheet metal weir structures in the levees or by manipulating the turnouts or control structures in the irrigation ditch.

When one series of basins has been completely flooded, the other series are then flooded in like manner.

Maintaining the flood.--The design depth of flood is maintained on all basins simultaneously by adding water at the rate needed to overcome losses due to evaporation, transpiration, deep percolation, and seepage through the levees.

Removing the flood.--Near the end of the flood maintenance period the water is cut off and the flood allowed to infiltrate the soil profile so that only a minimum remains to be drained off as waste. All water should be removed from the field about 2 weeks before the rice harvest to provide a dry surface for harvesting machinery.

Water Use Efficiency

As in other surface methods of irrigation, the efficiency of water use obtained with the contour-levee method depends on the physical characteristics of the soil, adequacy of land preparation, planning and construction of the system, and care exercised in its operation. Assuming good planning, construction, and operation, 65 to 70 percent efficiency may be obtained in irrigating crops other than rice. Different degrees of efficiency are obtainable for the three separate operations used in irrigating rice. When these are averaged, the overall efficiency is 70 to 80 percent.

Sample Design Problems

The design procedure for contour-levee irrigation systems is presented here by sample calculations. Those selected consist of designing combined contour-levee irrigation and drainage systems--one for cotton and one for rice--for a 60-acre field in the delta area of Louisiana (fig. 6-4). The surface of the field has been improved by land leveling. The design procedure for irrigating cotton is presented in sample calculation 3 and for rice in sample calculation 4.

Sample calculation 3.--Designing contour-levee irrigation and drainage system for cotton irrigation

Given:

A 60-acre field of cotton (A).....	A = 60 acres
Available stream size = 1,500 gpm.....	Q = 3.33 cfs
Net depth of application.....	F_n = 2.5 in.
Maximum time allowed for one irrigation.....	f = 8 days
Hours of operation (daylight only).....	h = 12 to 14 hr
Soil intake characteristics.....	See figure 6-3
Vertical interval between levees, 0.2 ft.....	vi = 2.4 in.

Find:

Minimum required stream per acre, q
Maximum size of basin
Required number of basins
Time required for one irrigation
Application efficiency
Irrigation ditch sizes
Drainage requirements
Turnout and culvert sizes

Procedure:

In figure 6-3 find the time (T_n) required for the net depth of application (F_n = 2.5 in.) to infiltrate the soil. T_n is 580 minutes.

Using figure 6-3 and allowing one-fourth T_n, or 145 minutes, to cover one unit or basin, find the average depth of water that infiltrates the soil during this period. Average time = $\frac{145}{2}$ = 72.5 minutes. This depth is 0.76 inch.

Average depth of water in surface storage at the end of time period

$\frac{T_n}{4}$ is 1/2 vi or $\left(\frac{2.4}{2}\right)$ or 1.2 inches

Minimum required stream size per acre (q):

$$q = \frac{(0.76 \text{ in.} + 1.2 \text{ in.})\ 60}{145 \text{ min}} = 0.811 \text{ acre-in. per hr}$$
(0.811 cfs per acre)

Maximum size of basin or unit area:

$$\frac{\text{Available stream size}}{\text{Minimum stream size per acre}} = \frac{3.33 \text{ cfs}}{0.811 \text{ cfs per acre}}$$
$$= 4.11 \text{ acres}$$

Required number of basins: $= \frac{60 \text{ acres}}{4.11 \text{ acres}} = 14.6$

Thus the 60-acre field is divided into 15 basins of 4 acres each, each requiring a minimum stream size of

4 acres x 0.811 acre-in. per hr or 3.24 acre-in. per hr
(3.24 cfs)

The available stream size of 3.33 cubic feet per second exceeds the minimum and will be used.

Time required for one irrigation

The average intake-opportunity time for one basin is equal to the average of the time at the lower edge (580 min + 145 min = 725 min) and at the upper edge (580 min), or 652 minutes.

In figure 6-3 find the average depth of application at time equal to 652 minutes. This is 2.7 inches. Check to see if the inflow stream (Q = 3.33 cfs) will irrigate the entire area within the allowable time, f = 8 days.

Determine the number of basins which can be irrigated per day within the allowable time of 12 to 14 hours with the stream (Q = 3.33 cfs).

Total volume of water required per basin for the average depth of application = 4 acres x 2.7 inches = 10.8 acre-inches.

The volume of water required for surface storage in one basin is 4 acres x 1.2 inches or 4.8 acre-inches. Depending on the irrigation sequence and arrangement of basins and ditches, some of the surface storage may be reused on lower basins. It is assumed here that the surface storage from two-thirds of the basins (10 in this example) may be drained off and used on lower basins. It is assumed also that 100 percent of the volume of water drained from the 10 basins is available for filling lower basins.

To fill three typical 4-acre basins only one requires filling the storage volume (4.8 acre-inches) from the "fresh" supply. Calculate time required to fill a series of basins as follows:

One basin $\frac{10.8 \text{ acre-in.} + 4.8 \text{ acre-in.}}{3.33 \text{ acre-in. per hr}} = 4.7 \text{ hr}$

Two basins $\frac{2(10.8 \text{ acre-in.}) + 4.8 \text{ acre-in.}}{3.33 \text{ acre-in. per hr}} = 7.9 \text{ hr}$

Three basins $\frac{3(10.8 \text{ acre-in.}) + 4.8 \text{ acre-in.}}{3.33 \text{ acre-in. per hr}} = 11.2 \text{ hr}$

The actual time to complete an irrigation of three basins depends on management of the drained water. The first basin can be drained of surface storage after 12.1 hours and the second 16.8 hours after water starts to fill the first basin.

Thus three basins could be irrigated within the allowable time, 12 to 14 hours.

In figure 6-4, each of the three segments of the field contains five basins.

Each series can be irrigated in 2 days--two basins in 1 day and three the next. The 15 basins (60 acres) can be irrigated in 6 days, which is within the allowable time, f = 8 days.

Determine field application efficiency in percent (E).

$$E = \frac{\text{Volume needed to refill soil} \times 100}{\text{Volume actually applied}}$$

The volume needed to refill the soil in one basin is 4 acres x 2.5 inches, or 10 acre-inches.

Efficiency when two basins (8 acres) are irrigated:

$$E = \frac{(2 \times 10 \text{ acre-in.}) \times 100}{(2 \times 10.8 \text{ acre-in.}) + 4.8 \text{ acre-in.}}$$

$$= \frac{20 \times 100}{26.4} = 76 \text{ percent}$$

Efficiency when three basins (12 acres) are irrigated:

$$E = \frac{(3 \times 10 \text{ acre-in.}) \times 100}{(3 \times 10.8 \text{ acre-in.}) + 4.8 \text{ acre-in.}}$$

$$= \frac{30 \times 100}{37.2} = 81 \text{ percent}$$

Average application efficiency for the 60-acre field:

$$\frac{3 \times 8 \text{ acres}}{60 \text{ acres}} (76 \text{ percent}) + \frac{3 \times 12 \text{ acres}}{60 \text{ acres}} (81 \text{ percent})$$

$$\text{Average } E = 0.4\ (76 \text{ percent}) + 0.6\ (81 \text{ percent}) = 79 \text{ percent}$$

Since the time required to apply the needed depth of water is within the time allowable and the field application efficiency is within acceptable limits, the irrigation phase of the design is satisfactory.

Irrigation ditch design

The required capacity of the irrigation field ditch shown in section B-B, figure 6-5, is equal to the available stream size or 3.33 cubic feet per second. A ditch with a bottom width of 1 foot, a depth of 2.2 feet, side slopes of 1-1/2 to 1, on a hydraulic gradient of 0.000125 foot per foot and an "n" value of 0.045 will have a capacity of 3.59 cubic feet per second, thus meeting this requirement.

Drainage requirements

The required capacities of the drainage ditches shown in figure 6-4 are computed using the applicable drainage coefficient curve (fig. 6-6). The required capacities are:

Ditch	Reach	Drainage area[1]	Required
		Acres	*Cubic feet per second*
Outlet A	Below 13+20	260	19.0
Drainage A	0+00 to 13+20	160	12.5
Lateral B	0+00 to 17+10	60	5.6
Lateral C	0+00 to 22+50	80	7.0
Interior drainageways	All	20	[2] 2.3
			3.33

[1] See drainage areas on figure 6-4.

[2] Since the irrigation stream (3.33 cfs) is larger than the required drainage capacity (2.3 cfs), 3.33 cfs is used for design purposes.

By using Corps of Engineers hydraulic tables, we find that a minimum-size ditch with the following dimensions carries 20 cubic feet per second with a hydraulic gradient of 0.0005 foot per foot and an "n" value of 0.04.

Bottom width, 3 feet; depth, 3 feet; side slopes, 1 to 1

This minimum-size ditch will thus meet the capacity requirements for the outlet ditch A and laterals B and C (fig. 6-4).

Turnout and culvert design

The required capacity of turnouts and culverts must be equal to the irrigation stream of 3.33 cubic feet per second. Sizes are determined by the formula, $Q = Ca\sqrt{2gh}$.

C = Coefficient of discharge
a = Area of opening square feet
g = Acceleration of gravity, feet per second
h = Available head in feet

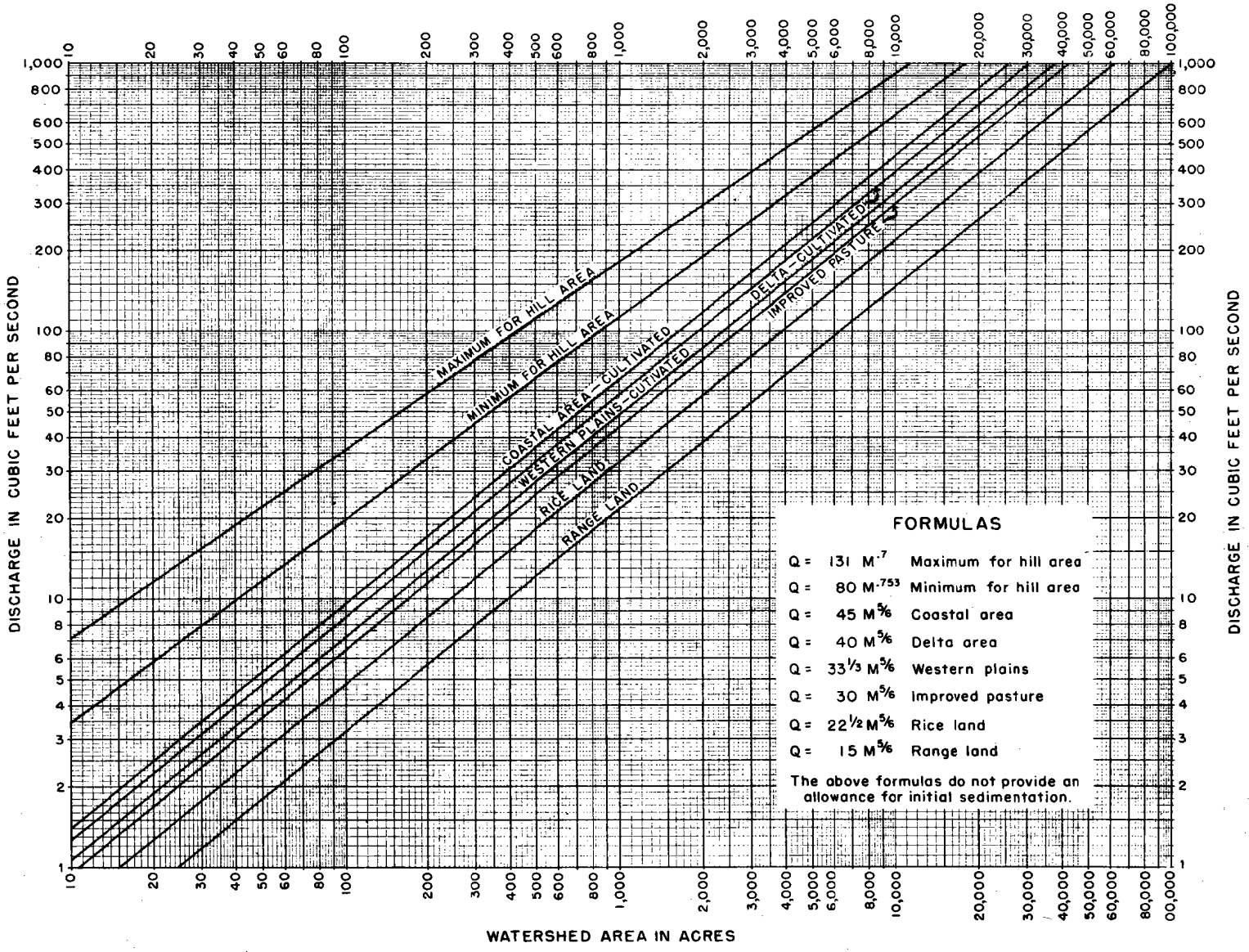


Figure 6-6.--Drainage-coefficient curves for Southwest.

Try using an 18-inch concrete pipe, 10 feet long, with a square-cornered entrance operating under a head of 0.1 foot. The computation becomes:

$$Q = 0.81 \times 1.767 \sqrt{2 \times 32.2 \times 0.1}$$
$$= 3.63 \text{ cubic feet per second (satisfactory)}$$

Interior irrigation ditches and drainageways

The required capacity of the combined irrigation ditches and drainageways shown in sections C-C and D-D of figure 6-5 must be equal to the available irrigation stream or 3.33 cubic feet per second.

First, determine the slope(s) of the hydraulic gradient in the ditches. This is the difference between the vertical interval (vi) between levees and the head (h) required on the control structure divided by the horizontal distance between levees (l) or,

$$s \quad \frac{vi - h}{l} = \frac{0.2 \text{ ft} - 0.1 \text{ ft}}{264 \text{ ft}} = 0.000375 \text{ ft per ft}$$

The design of the ditch or ditches is:

Depth, d	=	1.7 ft
Bottom, b	=	0, V-type
Side slopes	=	2 to 1
Area A	=	5.78 sq ft
Hydraulic radius, r	=	0.76
Roughness coefficient, n	=	0.04
Slope, s	=	0.000375 ft per ft
Velocity, v	=	0.60 fs
Capacity, Q	=	3.47 cfs (satisfactory)

Sample calculation 4.--Designing contour-levee irrigation and drainage system for rice irrigation

Given:

A 60-acre field of rice (A).....	A = 60 acres
Available stream size = 2,400 gpm.....	= 5.35 cfs
Available water holding capacity of soil at root zone depth (18 in.).....	= 3.6 in.
Saturated moisture capacity of soil at root zone depth.....	= 7.35 in.
Permeability of restricting layer.....	= 0.002 in. per hr
Net depth of application (from irrigation guide).....	F_n = 1.8 in.
Depth of flood.....	= 3 in.
Maximum time allowable for one irrigation...	f = 6 days
Hours of operation (continuous).....	h = 24 hr
Soil intake characteristics.....	See figure 6-3
Peak-period consumptive-use rate.....	u = 0.3 in. per day
Vertical interval between levees.....	vi = 2.4 in.

Find:

Minimum required stream per acre, q
Maximum size of basin
Required number of basins
Time required for one irrigation
Application efficiency
Irrigation ditch sizes
Drainage requirements
Turnout and culvert sizes
Control structure dimensions
Height of levees

Procedure:

Moisture control for germination.--Using figure 6-3, find the time (T_n) required for the net depth of application (F_n = 1.8 in.) to infiltrate the soil. T_n is 345 minutes.

Using figure 6-3, and allowing one-fourth of T_n, or 86 minutes, to cover one basin, find the average depth of water that infiltrates the soil during this period. This depth is 0.62 inch at the average time $\frac{86}{2}$ or 43 min.

Average depth of water in surface storage at the end of $T_{n/4}$:

$$1/2 \text{ vi } (1/2(2.4)) = 1.2 \text{ in.}$$

Minimum required stream size per acre (q):

$$q = \frac{(0.62 \text{ in.} + 1.2 \text{ in.})\ 60}{86 \text{ min}} = 1.27 \text{ acre-in. per hr}$$
$$= 1.27 \text{ cfs per acre}$$

Maximum size of basin:

$$\frac{\text{Available stream size}}{\text{Minimum stream size per acre (q)}} = \frac{5.35 \text{ cfs}}{1.27 \text{ cfs per acre}} = 4.21 \text{ acres}$$

$$\text{Required number of basins} = \frac{60 \text{ acres}}{4.21} = 14.25$$

Thus the 60-acre field is divided into 15 basins of 4 acres each. Minimum-size stream for a 4-acre basin

$$q = 4 \text{ acres} \times 1.27 \text{ acre-in. per hr} = 5.08 \text{ acre-in. per hr}$$
$$= 5.08 \text{ cfs}$$

The available stream size of 5.35 cubic feet per second exceeds the minimum and is used.

The average intake opportunity time for one basin is equal to average of the time at the lower edge (345 min + 86 min = 431 min) and at the upper edge (345 min), or 388 minutes.

In figure 6-3 find the average depth of application at time equal to 388 minutes. This is 1.95 inches. Check to see if the inflow stream (Q = 5.35 cfs) will irrigate the entire area within the allowable time of f = 6 days.

The total volume of water required per basin for the average depth of application is 4 acres x 1.95 inches or 7.8 acre-inches.

The volume of water required for surface storage in one basin is 4 acres x 1.2 inches or 4.8 acre-inches. For a series of five basins, the surface storage volume that may be reused by draining to a lower basin depends on the arrangement of basins, sequence of irrigation, and loss by deep percolation.

Assume that the 1.2 inches required to cover a basin in a series of five basins is available for reuse from three of the five basins. Then the total storage required is 4 acres x 1.2 inches x 2 basins or 9.6 acre-inches.

Time required to fill one basin:

$$\frac{7.8 \text{ acre-in.} + 4.8 \text{ acre-in.}}{5.35 \text{ acre-in. per hr}} = 2.36 \text{ hr}$$

Time required to fill a series of five basins:

$$\frac{5(7.8 \text{ acre-in.}) + 9.6 \text{ acre-in.}}{5.35 \text{ acre-in. per hr}} = 9.08 \text{ hr}$$

Minimum time required to fill the three series of five basins is

3 x 9.08 hr = 27.3 hr or 1.13 days .

As in the preceding example, the actual time required to complete the irrigation of a series of basins and the entire field depends on management of the drained water. The first basin in a series of five basins is ready to drain of surface storage 7.2 hours after water is turned into the series. To complete the irrigation of all 15 basins takes about 33 hours--well within the 6-day period available.

Determine the field application efficiency in percent (E):

$$E = \frac{\text{Volume needed to refill soil x 100}}{\text{Volume actually applied}}$$

The volume needed to fill the soil in one basin is

4 acres x 1.8 in. or 7.2 acre-in.

Efficiency when a series of five basins (20 acres) is irrigated:

$$E = \frac{(5 \times 7.2 \text{ acre-in.}) \times 100}{(5 \times 7.8 \text{ acre-in.}) + (9.6 \text{ acre-in.})} = 74 \text{ percent}$$

This field application efficiency applies to the entire 60-acre field.

Flooding.--Find the time required for depletion of one-half the available soil moisture:

$$\frac{1/2 \times 3.6 \text{ in.} \times 24 \text{ hr}}{0.3 \text{ in. per day}} = 144 \text{ hr}$$

Find the depth of application required to produce a 3-inch flood over the design area:

Depth required to saturate the soil.....	=	7.35 in.
One-half vertical interval between levees.....	=	1.20 in.
Deep percolation losses (144 hr x 0.002 in. per hr)....	=	0.29 in.
Depth of flood.....	=	3.00 in.
Total application.....	=	11.84 in.

Find the minimum required irrigation stream:

$$Q = \frac{60 \text{ acres} \times 11.84 \text{ in.}}{144 \text{ hr}} = 4.93 \text{ acre-in. per hr}$$
$$= 4.93 \text{ cfs}$$

The available irrigation stream (5.35 cfs) exceeds the minimum and will be used.

Find the time required to flood the entire field:

$$\frac{60 \text{ acres} \times 11.84 \text{ in.}}{24 \times 5.35 \text{ acre-in. per hr}} = 5.53 \text{ days}$$

The time required is within the allowable time, f = 6 days.

Maintaining the flood.--Find the minimum irrigation stream required to maintain the flood:

$$Q = 60 \text{ acres} \left(\frac{0.3 \text{ in. per day}}{24 \text{ hr}} + 0.002 \text{ in. per hr} \right)$$
$$= 0.87 \text{ acre-in. per hr}$$
$$= 0.87 \text{ cfs}$$

Irrigation ditch design

The required capacity of the irrigation field ditch shown in section B-B, figure 6-5, is equal to the available stream size or 5.35 cubic feet per second. A ditch with a bottom width of 1 foot, a depth of 2.6 feet,

side slopes of 1-1/2 to 1, on a hydraulic gradient of 0.000125 foot per foot, and having an "n" value of 0.045 has a capacity of 5.38 cubic feet per second, thus meeting this requirement.

Drainage requirements

The drainage requirements, ditch sizes and capacities, are the same as those shown in sample calculation 3.

Turnout and culvert size

The required capacity of turnouts and culverts must be equal to the available irrigation stream or 5.35 cubic feet per second. Sizes are determined by the formula, $Q = Ca \sqrt{2gh}$.

Try using a 21-inch concrete pipe, 10 feet long, with a square-cornered entrance operating under a head of 0.12 foot. The computation becomes:

$$Q = 0.80 \times 2.405 \sqrt{2 \times 32.2 \times 0.12}$$
$$= 5.35 \text{ cfs (satisfactory)}$$

Interior irrigation ditches and drainageways

The required capacity of the combined irrigation ditches and drainageways shown in sections C-C and D-D of figure 6-5 must be equal to the available irrigation stream or 5.35 cubic feet per second.

First, determine the slope(s) of the hydraulic gradient in the ditches. This is the difference between the vertical interval (vi) between levees and the head (h) required on the control structure divided by the horizontal distance between levees (l) or,

$$s = \frac{vi - h}{l} = \frac{0.2 \text{ ft} - 0.12 \text{ ft}}{264 \text{ ft}} = 0.000303 \text{ ft per ft}$$

The design of the ditch or ditches is:

Depth, d	=	2.1 ft
Bottom, b	=	0, V-type
Side slopes	=	2 to 1
Area, A	=	8.82 sq ft
Hydraulic radius, r	=	0.939
Roughness coefficient, n	=	0.040
Slope, s	=	0.000303 ft per ft
Velocity, v	=	0.621 cs
Capacity, Q	=	5.48 cfs (satisfactory)

Control structure dimensions

For rice and other close-growing crops, the water level in each basin is often controlled by a weir placed in the levee along the lower side of the basin. These weir structures are usually made of sheet metal or some other suitable material and are located near an access road for convenience. They are generally designed to operate under a head of 0.2 to 0.25 foot. When these structures are used, the operating head must be considered in determining the height of the levees.

The weirs are made of sheet metal and are designed to have a capacity equal to the available stream capacity or 5.35 cubic feet per second. The formula for determining weir dimensions is:

$$Q = CLH^{3/2} \text{ or } H = \left(\frac{Q}{CL}\right)^{2/3}$$

With the value of C = 3.2, try crest length L = 14 feet and solve for the operating head:

$$H = \left(\frac{5.35}{3.2 \times 14}\right)^{2/3} = 0.24 \text{ ft (satisfactory)}$$

Height of levees

Vertical interval between levees.....	0.20 ft
Depth of flood (3 in.).....	.25 ft
Head on weir control structure.....	.24 ft
Freeboard provided.....	.30 ft
Allowance for settlement.....	.30 ft
Constructed height.....	1.29 ft
say	1.3 ft

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Section 15

Irrigation

Chapter 7

Trickle Irrigation

Contents

	Page
Preface	vi
Description	7-1
Types of systems	7-1
Drip	7-1
Subsurface	7-2
Bubbler	7-2
Spray	7-2
Advantages	7-2
Water and farm operation cost savings	7-2
Use of saline water	7-3
Use of rocky soils and steep slopes	7-3
Disadvantages	7-4
Cost	7-4
Clogging	7-4
Lack of uniformity	7-4
Salt accumulation	7-4
Other hazards	7-4
Benefits obtained and safeguards required with fertilizer and chemical injections	7-5
Fertilizer	7-5
Nitrogen	7-5
Phosphorus	7-6
Potassium	7-6
Trace elements	7-6
Chemicals to control precipitates and organic deposits	7-6
Calcium and iron	7-6
Algae and slime	7-6
Iron bacteria	7-7
Treatment for precipitates, algae, and slime	7-7
System components	7-8
Control head	7-8
Pumping station	7-8
Water-measuring devices	7-8
Fertilizer and chemical injection equipment	7-8
Valves	7-9
Sediment removal	7-9
Main and submain lines	7-13
Manifolds	7-13
Laterals	7-13
Emitters	7-15
Flow controls and pressure regulators	7-15
Hand-operated pressure controls and on-off valves	7-18
Sequential operation	7-18
Partial automation	7-18
Full automation	7-18
Operation and maintenance	7-19
Soil-plant-water considerations	7-20
Area wetted	7-20
Percent area wetted	7-22
Meeting irrigation water requirements	7-23
Maximum net depth of application	7-23
Consumptive use rate	7-24

Page
Seasonal transpiration . . . 7-24
Net depth of application . . . 7-24
Gross water application . . . 7-24
Seasonal irrigation efficiency . . . 7-25
Gross seasonal depth of application . . . 7-25
Gross seasonal volume . . . 7-26
Plant response . . . 7-26
Optimum moisture levels . . . 7-26
Salinity control . . . 7-27
Crop tolerance and yield . . . 7-27
Leaching requirement . . . 7-27
Design procedures . . . 7-29
Design criteria . . . 7-29
Emitter selection criteria . . . 7-30
General suitability . . . 7-31
Sensitivity to clogging . . . 7-31
Manufacturing variation . . . 7-32
System coefficient of manufacturing variation . . . 7-32
Relation of pressure to discharge . . . 7-33
Relation of temperature to discharge . . . 7-34
Connection losses . . . 7-34
Performance . . . 7-34
Discharge exponent . . . 7-35
Types of emitters . . . 7-36
Long-path emitters . . . 7-36
Tortuous- and short-path emitters . . . 7-37
Orifice emitters . . . 7-37
Twin-chamber tubing . . . 7-37
Vortex emitters and sprayers . . . 7-37
Compensating emitters . . . 7-37
Flushing emitters . . . 7-38
Emitter operating characteristics . . . 7-38
Discharge . . . 7-38
Average pressure . . . 7-39
Emission uniformity . . . 7-39
Allowable pressure-head variation . . . 7-40
Total system capacity . . . 7-42
Pump operating time per season . . . 7-42
Net water-application rate . . . 7-43
Computing injection of fertilizer and chemicals . . . 7-43
Pipeline hydraulics . . . 7-44
Friction loss in pipelines . . . 7-44
Head losses through fittings . . . 7-46
Multiple-outlet pipeline losses . . . 7-47
Dimensionless pipe-friction curve . . . 7-47
Economic pipe-size selection . . . 7-48
Life-expectancy costs . . . 7-49
Economic pipe-selection charts . . . 7-52
Lateral line design . . . 7-54
Characteristics . . . 7-54
Spacing of manifolds . . . 7-56

Page

Location of manifolds . . . 7-56
Pressure difference . . . 7-57
Manifold design . . . 7-58
Characteristics . . . 7-58
Economic-chart design method . . . 7-60
General graphical-design method . . . 7-64
Alternative graphical-design method . . . 7-69
Estimating pressure loss from pipe friction . . . 7-70
Locating the H_m line and estimating $\triangle H'_m$ . . . 7-70
Sample designs for trickle irrigation systems . . . 7-71
Drip system . . . 7-71
Design factors . . . 7-71
Lateral line design and system layout . . . 7-76
Manifold design . . . 7-79
Main-line design . . . 7-81
Total dynamic head . . . 7-83
System design summary . . . 7-83
Spray system . . . 7-84
Design factors . . . 7-84
Lateral line design and system layout . . . 7-88
Manifold design . . . 7-89
Main-line design . . . 7-93
Total dynamic head . . . 7-94
System design summary . . . 7-94
Line-source system . . . 7-94
Design factors . . . 7-96
Lateral line design and system layout . . . 7-98
Manifold design . . . 7-98
Main-line design . . . 7-100
Total dynamic head . . . 7-100
System design summary . . . 7-100
Field evaluation . . . 7-101
Equipment needed . . . 7-101
Field procedure . . . 7-101
Using field data . . . 7-102
Average depth of application . . . 7-102
Volume per day . . . 7-106
Emission uniformity . . . 7-106
Gross application required . . . 7-107
Application efficiencies . . . 7-107
Appendix A—Nomenclature . . . 7-109
Appendix B—Pipe friction-loss tables . . . 7-113
Appendix C—List of equations . . . 7-126

Figures

		Page
7–1	In-line drip emitter	7-1
7–2	Drip system for grapes, leaving much of soil surface dry	7-2
7–3	Drip system on slope of avocado ranch	7-3
7–4	Typical soil moisture pattern under trickle irrigation, showing salt accumulation	7-4
7–5	Basic components of a trickle irrigation system	7-8
7–6	Pressure-differential injection system	7-9
7–7	Valves at the head of a trickle irrigation system	7-9
7–8	Effect of flow rate on the maximum particle size passing through a typical free-flow sand filter with media of various sizes	7-12
7–9	Manifold layout showing inlet connection uphill from center and showing pressure-regulated manifolds	7-13
7–10	Various lateral layouts for a widely spaced permanent crop	7-14
7–11	Single-exit long-path emitter	7-16
7–12	Multiexit long-path emitter	7-16
7–13	Single-exit orifice-type emitter	7-16
7–14	Orifice-vortex-type emitter	7-16
7–15	Twin-wall emitter lateral	7-16
7–16	Flushing-type emitter	7-17
7–17	Typical means for connecting emitters to laterals	7-17
7–18	Wetting pattern profiles for equal volumes (12 gal) of water applied at three rates to a dry sandy soil	7-21
7–19	Relationship between vertical and horizontal water movement in a dry sandy soil for various amounts of water and various application rates	7-21
7–20	Idealized wetting patterns in a homogeneous fine sandy soil under a drip and a spray emitter	7-22
7–21	Hypothetical relation of potential production to percent area wetted	7-23
7–22	Discharge variations resulting from pressure changes for emitters with various discharge exponents (x)	7-33
7–23	Emitter-connection loss (f_e) values for various sizes of barbs and inside diameters of laterals	7-34
7–24	Graphical method for determining the discharge exponent (x) in a sample calculation	7-36
7–25	Cross section of a long-path emitter that can be opened for easy cleaning	7-36
7–26	Cross section of a continuous-flushing emitter	7-38
7–27	Typical two-station split-flow layout for trickle irrigation system with Blocks I and III, or II and IV, operating simultaneously	7-39
7–28	Distribution of a pressure head in a subunit	7-41
7–29	Combined effect of pressure-head and manufacturing variations on discharges of individual emitters	7-41
7–30	Darcy-Wisbach f-values for 1/2-in. (0.58-in. inside diameter) trickle irrigation hose	7-45
7–31	General friction curve for a multioutlet pipeline that has uniform diameter, uniform spacing between outlets, and uniform flow per outlet	7-48
7–32	Influence of pipe size on fixed, power, and total costs	7-49
7–33	Economic pipe-size selection chart for polyvinyl chloride thermoplastic IPS (iron pipe size) pipe having minimum acceptable standard SDR (standard dimension ratio) ratings	7-50
7–34	Dimensionless sketch showing terms used in numerical solution of optimum position for manifold	7-57
7–35	Graph for selecting location of inlet to a pair of tapered manifolds on a slope	7-59
7–36	Standard manifold friction curves for 2-gpm outlet every 20 ft.	7-62
7–37	Standard manifold friction curves for 6-gpm outlet every 60 ft.	7-63
7–38	Graph for determining manifold pipe-friction adjustment factors for trapezoidal subunits	7-65
7–39	Dimensionless manifold friction curves scaled to represent manifold flow rate (q_m) = 178 gpm through each size of pipe	7-66
7–40	Overlay for design of manifolds (1), (2), and (3) using the general graphical-design method	7-67

Page

7–41 Friction curve overlay to demonstrate graphical method using a standard manifold curve for designing a tapered manifold for a steep slope 7-68
7–42 Friction curve overlay demonstrating the graphical solution for using standard manifold curves to design tapered manifolds with a given allowable manifold pressure variation $(\triangle H_m)_a$ 7-70
7–43 Drip-system data for a deciduous orchard in the Central Valley of California 7-72
7–44 Orchard layout with sample design for a drip irrigation system 7-73
7–45 Drip-system design factors for a deciduous orchard in the Central Valley of California 7-74
7–46 Friction curve overlay to demonstrate graphical solution of manifold positioning and $\triangle h$ (difference in pressure head along the lateral) 7-77
7–47 Friction curve overlay to demonstrate graphical solution for determining manifold friction loss (H_f) for a drip system 7-81
7–48 Spray-system data for a citrus grove in Florida 7-85
7–49 Citrus grove with spray irrigation system 7-86
7–50 Spray-system design factors for a citrus grove in Florida 7-87
7–51 Plot of spray diameter vs. emitter pressure developed from manufacturer's data for 0.04-in.-diameter orifice 7-88
7–52 Friction curve overlay to demonstrate graphical solution for determining manifold friction loss (H_f) for a spray system 7-90
7–53 Line-source-system data for Texas tomato field 7-95
7–54 Tomato field with line-source drip irrigation 7-96
7–55 Line-source-system design factors for Texas tomato field 7-97
7–56 Form for evaluation data 7-103
7–57 Field measurement of discharge from an emitter 7-106

Tables

7–1 Cycling method characteristics of a trickle irrigation system 7-17
7–2 Estimates of area wetted (A_w) in various soils 7-20
7–3 Seasonal transpiration ratios for arid and humid regions with various soil textures and rooting depths 7-26
7–4 Minimum (min) and maximum (max) values of EC_e for various crops 7-28
7–5 Test characteristics of emission devices 7-35
7–6 Reduction coefficient (F) for multiple-outlet pipeline friction-loss computations in which the first outlet is a full spacing from the pipe inlet 7-47
7–7 Dimensionless data for plotting friction curves for multiple-outlet pipelines 7-49
7–8 Present-worth and annual economic factors for an assumed 9-percent annual rise in energy costs with various interest rates and life expectancies 7-51
7–9 Scaled values of $\triangle H_m/(L/100)$ for constructing a set of dimensionless manifold friction-loss curves for manifold flow rate (q_m) = 178 gpm and reduction coefficient to compensate for discharge (F) = 0.38 7-65
7–10 Scalar ratios (JF') for constructing dimensionless curves of x/L vs. $\triangle H_m/(L/100)$ for various field-shape factors (S_f) 7-66

Preface

Experimental efforts in trickle irrigation date back to the 1860's, but it was not until the mid-1960's, after the development and wide availability of low-cost plastic pipe and fittings, that commercial trickle irrigation became feasible. Today trickle-irrigated croplands and orchards amount to more than 800 thousand acres worldwide, including more than 100 thousand acres in the United States.

This chapter of the National Engineering Handbook describes design procedures for trickle irrigation systems. It covers logical design procedures for the major types of trickle irrigation systems in current use and contains detailed, complete sample designs. The chapter is written for engineers and experienced technicians; however, it should also be of value to others interested in the design and application of trickle irrigation systems.

Chapter 7
Trickle Irrigation

Description

Trickle irrigation is the slow application of water on or beneath the soil surface by drip, subsurface, bubbler, and spray systems. Water is applied as discrete or continuous drops, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line. Water is dissipated from a pipe distribution network under low pressure in a predetermined pattern. The outlet device that emits water to the soil is called an "emitter." The shape of the emitter reduces the operating pressure in the supply line, and a small volume of water is discharged at the emission point. Water flows from the emission points through the soil by capillarity and gravity.

Types of Systems

Drip

In drip irrigation, water is applied slowly to the soil surface as discrete or continuous drops or tiny streams through small openings (fig. 7–1). Discharge rates are less than 3 gallons per hour (gph) for widely spaced individual applicators and less than 1 gph/ft for closely spaced outlets along a tube (or porous tubing).

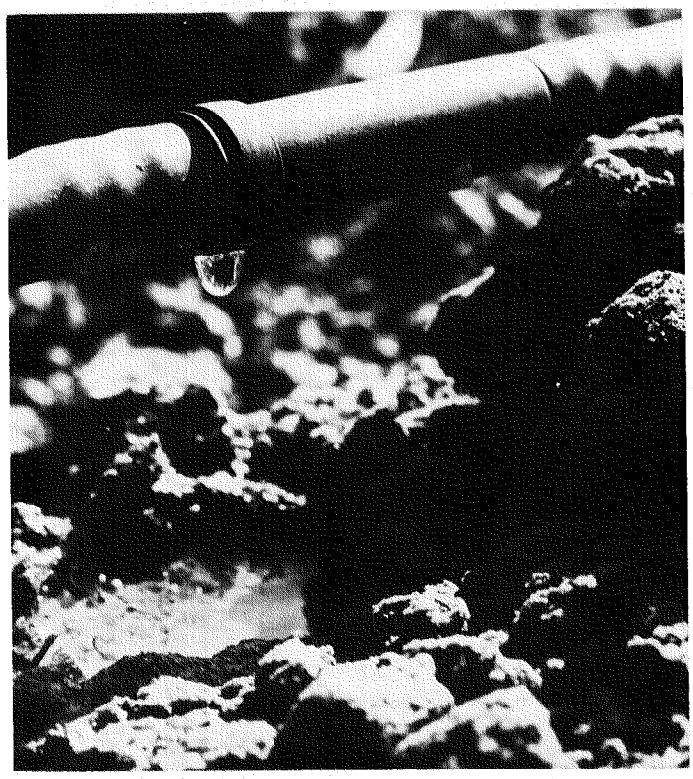


Figure 7–1.—In-line drip emitter.

Subsurface

In subsurface irrigation, water is applied slowly below the soil surface through emitters with discharge rates in the same range as those for drip irrigation. This method of application is not to be confused with subirrigation, in which the root zone is irrigated through or by water table control.

Bubbler

In bubbler irrigation, water is applied to the soil surface in a small stream or fountain from an opening with a point discharge rate greater than that for drip or subsurface irrigation but less than 1 gallon per minute (gpm). The emitter discharge rate normally exceeds the infiltration rate of the soil, and a small basin is required to control the distribution of water.

Spray

In spray irrigation, water is applied to the soil surface as a small spray or mist. The air is instrumental in distributing the water, whereas in drip, bubbler, and subsurface irrigation, the soil is primarily responsible for distributing the water. Discharge rates in spray irrigation are lower than 30 gph.

Advantages

Trickle irrigation is a convenient means of supplying each plant, such as a tree or vine, with a low-tension supply of soil moisture sufficient to meet evapotranspiration demands. A trickle irrigation system offers unique agronomic, agrotechnical, and economic advantages for efficient use of water and labor.

Water and Farm Operation Cost Savings

Trickle irrigation can reduce water loss and operating costs because only the amount of water required by the crop is applied. Labor costs for irrigating are reduced because trickle systems are equipped with automatic timing devices.

Much of the soil surface remains dry with trickle irrigation (fig. 7–2); this has two benefits. First,

Figure 7–2.—Drip system for grapes, leaving much of soil surface dry.

weed growth is reduced, so labor and chemical costs for weed control are reduced. Second, uninterrupted orchard operations are possible, and with row crops on beds, the furrows remain relatively dry and provide firm footing for farm workers.

Fertilizers and pesticides can be injected into the irrigation water to avoid the labor needed for their ground application. Several highly soluble materials are available, and new products that widen the choice are being introduced. Greater control over fertilizer placement and timing through trickle irrigation may improve fertilization efficiency.

Use of Saline Water

Frequent irrigation maintains a stable soil moisture condition that keeps salts in soil water more dilute. Thus it is possible to irrigate with water of higher salinity.

Use of Rocky Soils and Steep Slopes

Trickle irrigation systems can be designed to operate efficiently on almost any topography. Systems are operating on avocado ranches that are almost too steep to harvest (fig. 7–3). Because the water is applied close to each tree, rocky areas can be trickle irrigated effectively even when tree spacing is irregular and tree size varies.

Figure 7–3.—Drip system on slope of avocado ranch.

Disadvantages

The main disadvantages inherent in trickle irrigation systems are their comparatively high cost, proneness to clogging, tendency to build up local salinity, and, when they are improperly designed, spotty distribution pattern.

Cost

Trickle irrigation systems are expensive because of their requirements for large quantities of piping and filtration equipment to clean the water. System costs can vary considerably depending on the crop, terrain, and quantity of water available. Steep terrain may require several pressure regulators in the system. Because of spacing, some crops require less pipe than others. The degree of automation affects the cost. In general, the cost is far greater for a trickle system than for a sprinkler or flood system.

Clogging

Because the emitter outlets are very small, they can become clogged easily by mineral or organic matter particles. Clogging can reduce emission rates or upset uniformity of water distribution, and cause plant damage. In some instances, particles are not adequately removed from the irrigation water before it enters the pipe network. In others, particles may form in water as it stands in the lines or evaporates from emitter openings between irrigations. Iron oxide, calcium carbonate, algae, and microbial slimes form in irrigation systems in certain locations. Chemical treatment and proper filtration of water usually can prevent or correct emitter clogging.

Lack of Uniformity

Most trickle irrigation emitters operate at low pressures, 3 to 20 pounds per square inch (psi). If a field slopes steeply, the emitter discharge during irrigation may differ as much as 50 percent from the volume intended, and water in the lines may drain through lower emitters after the water is shut off. Some plants receive too much water; others receive too little.

Salt Accumulation

Salts tend to concentrate at the soil surface and constitute a potential hazard because light rains can move them into the root zone (fig. 7–4). When a rain of less than 2 in. falls after a period of salt accumulation, irrigation should continue on schedule to ensure that salts leach below the root zone.

During trickle irrigation, salts also concentrate below the surface at the perimeter of the soil volume wetted by each emitter (fig. 7–4). If this soil dries between irrigations, reverse movement of soil water may carry salt from the perimeter back toward the emitter. Water movement must always be away from the emitter to avoid salt damage.

Other Hazards

If uncontrolled events interrupt irrigation, crops can be damaged quickly because roots can extract nutrients and water only from the relatively small volume of soil wetted.

Rodents are known to chew polyethylene laterals. Rodent damage can be prevented by rodent control or use of polyvinyl chloride (PVC) laterals.

A main supply line can be broken, or the filtration system can malfunction and allow contaminants into the system. One filtration malfunction can result in the plugging of many emitters that then must be cleaned or replaced.

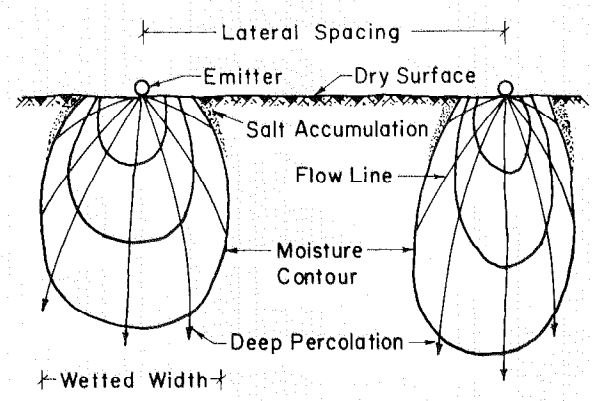


Figure 7–4.—Typical soil moisture pattern under trickle irrigation, showing salt accumulation.

Benefits Obtained and Safeguards Required with Fertilizer and Chemical Injections

Fertilizer

Very little of the fertilizer spread or broadcast over the soil surface moves into the root zone with trickle irrigation. Therefore, much of the required fertilizer, especially nitrogen, must be added directly in the water. Unfortunately, clogging problems are associated with the injection of various fertilizers into the irrigation water.

Fertilizer should always be injected over a period of 2 hr or more to maintain a reasonably uniform distribution, and it should be injected early enough in the irrigation cycle to permit flushing the system afterward.

Applying fertilizer in the irrigation water requires less labor and equipment than the conventional spreading methods. Also, conventional application of nutrients is difficult under trickle irrigation because of the small wetted volume. Slow-release fertilizer must be applied directly in the wetted area.

Many commercial fertilizers can be added during the growing season without damaging the system; thus, fertilizer levels can be maintained at an ideal level (even in sandy soils) throughout the growing season. Wetting a large percentage of the soil volume with root development throughout makes fertility management easier and takes advantage of the natural fertility of the soil.

The fertilizer program to be followed must be considered in designing a trickle system. Some types of fertilizers are not suitable for injection because of volatilization of gaseous ammonia, low water solubility, separation of the components in the mixture, leaching losses from application with excessive water, and problems with the quality of irrigation water. Therefore, the injection equipment must be designed with an understanding of the chemical composition of the fertilizer to be used. Also, the soil and water must be analyzed to determine whether the fertilizer compounds are suitable.

Following are some of the fertilizers commonly injected:

Nitrogen

Nitrogen is relatively problem free. Anhydrous ammonia (82–0–0) and aqua-ammonia (24–0–0) can be injected into irrigation water, but fertilizer efficiency is likely to be lost because of volatilization.

Another problem with ammonia injection has to do with the rise of hydroxide ion concentration in water. Ammonia increases the pH, which causes soluble calcium and magnesium to precipitate in the water and coat the inside of pipes and plug emitters. This kind of problem can be overcome by injecting a water softener ahead of the ammonia gas. The water softener complexes the calcium and magnesium and eliminates the problem, but it adds considerably to the cost of fertilization.

Most of the nitrogen salts and urea dissolve readily in water. But the nitrogen-containing fertilizers mentioned under phosphorus fertilization should not be considered highly soluble because of the interactions involving phosphorus in water and soil.

Ammonium sulfate (21–0–0) and ammonium nitrate (34–0–0) are very common fertilizer materials. In the former all the nitrogen is in the ammonium form, and in the latter about 26 percent by weight of the fertilizer is ammonium nitrogen and 8 percent is nitrate nitrogen. Urea (44–0–0) is a soluble nitrogen fertilizer. It is a neutral molecule that does not react with water to form ions. Urea and ammonium nitrate are mixed in water to give a fairly concentrated liquid mixture marketed as 30–0–0. When this mixture is injected into irrigation water, its individual components behave exactly like the dry materials dissolved and injected separately.

All of these nitrogen materials may be injected with no side effects in the water or irrigation system.

Both urea and nitrate nitrogen stay in solution in the soil and move with the soil water; therefore, these materials are highly susceptible to leaching if excessive water is applied. Ammonium nitrogen behaves quite differently. Because it is a positively charged ion, it enters into cation exchange reactions in the soil. A small change in either soluble constituent alters the relative amount of the ions in exchangeable form. In the exchangeable form, ammonium is immobile. Because cation exchange reactions are very rapid, ammonium applied in irrigation water is immobilized almost instantly on contact with soil and remains on or near the soil surface.

Ammonium applied in water readily converts to exchangeable ammonium and simultaneously generates an equivalent amount of cations in solution. In semiarid and arid regions, soils are naturally neutral to alkaline (pH 7 to 8.2), depending on how much free lime or calcium carbonate is present. In these kinds of soils, any exchangeable ammonium

that exits at the soil surface will likely volatilize. Ammonium is very sensitive to temperature and moisture. Water vaporizes very rapidly from soil after irrigation, and ammonium is especially susceptible to gaseous loss during this time.

Phosphorus

Phosphorus is difficult to apply by injection. Treble-superphosphate (TSP, 0–45–0), commonly used, is classified as water soluble but is only moderately so. Actual dissolution of TSP in water is limited because the monocalcium phosphate of TSP changes to dicalcium phosphate, which is insoluble in water. Therefore, treble-superphosphate is not suitable for injection.

Several kinds of ammonium phosphate are soluble in water. Ammonium phosphate sulfate (16–20–0), monoammonium phosphate (11–48–0), and diammonium phosphate (16–46–0) are suitable for injection when nitrogen and phosphorus are needed. Phosphoric acid is another form of soluble phosphorus.

The quality of the irrigation water must be considered before injecting phosphorus into a trickle irrigation system. If the irrigation water has a pH above 7.5 and a high calcium content, the injected phosphorus will precipitate as dicalcium phosphate, which can plug emitters and restrict flow in the pipeline network. In this situation, phosphoric acid must be used to meet phosphate needs. Flushing the system with a solution of either sulfuric or hydrochloric acid immediately after applying the phosphoric acid prevents clogging.

Organic phosphate compounds such as glycerophosphoric acid can be injected through trickle irrigation systems without fear of precipitation in the system. The organic compounds are comparable to urea in terms of their behavior in soils, but they are relatively expensive compared with the soluble forms of inorganic phosphorus, which are themselves relatively expensive compared with TSP. Phosphorus is immobile in soil because it becomes insoluble almost as soon as it contacts calcium in the soil. Therefore, phosphate applied by spray irrigation collects at the soil surface and is unavailable to the crop. Subsequent crops will be benefited, however, because the next plowing will mix the fertilizer throughout the plowed layer. Phosphorus applied by drip irrigation is concentrated at the application points; however, phosphate moves in the soil enough to reach the root zone.

Potassium

Potassium is easy to inject through a trickle irrigation system. Potassium oxide (the most common source) is very soluble. The fertilizer moves freely into the soil and is not readily leached away.

Trace Elements

The trace elements—magnesium, zinc, boron, iron, copper, etc.—also can be applied through a trickle irrigation system. Application rates must be based on analysis of soil and water because trace elements applied in excessive quantities can react with salts in the water and be toxic to plants.

If complete details for injecting trace elements into a trickle system have not been field checked, it is better to use conventional application methods, including foliar sprays or mechanical application and incorporation into the soil.

Chemicals to Control Precipitates and Organic Deposits

Precipitates can form inside the pipes and emitters from dissolved minerals that come out of solution if the pH or temperature changes. They are not the same as the mineral deposits that are left by evaporation and build up on the outside of emitters. These latter deposits usually are not a problem except possibly at the ends of exit tubes and valve faces. Clogging of emitters by precipitates and organic deposits cannot be prevented by filtration; chemicals must be injected into the system to control them.

Calcium and Iron

Calcium and iron precipitates are a potential problem with most well water. An analysis of well water will indicate whether the bicarbonate or iron concentration is high enough to be a problem. From general observations, a bicarbonate level higher than 2.0 milliequivalents per liter (meq/L) coupled with a pH above 7.5 indicates a potential problem.

Algae and Slime

Algae are microscopic plants that produce their own food through the conversion of light energy and nutrients. Algae are common in most surface water supplies. Because most algae need light to grow, growth inside the system by small algal particles

that pass through the filter can be deterred by use of black emitters and black pipe above ground. In the dark, bacteria break down the algal particles, which are then expelled through the emitters along with suspended silt and clay.

Slime is a generic term for the growth of long-filament microorganisms, primarily bacteria. These microorganisms do not produce their own food and do not require sunlight for growth. The more common are airborne; therefore, open systems are most susceptible.

Iron Bacteria

Iron is present in water in the soluble (ferrous) form. In the presence of oxygen, it is oxidized to the insoluble ferric form, a reddish-brown precipitate. Iron bacteria can produce enough slime to plug emitters if the water supply has an iron concentration of 0.3 parts per million (ppm) or greater and the pH is between 4.0 and 8.5.

Treatment for Precipitates, Algae, and Slime

Various types of chemicals can be injected into trickle irrigation systems to control calcium and iron precipitates and organic deposits.

Acid is the best treatment for bicarbonates resulting from calcium precipitation. The least expensive acid should be chosen and used at a concentration that will offset the excess bicarbonates. The amount of acid required and the optimum pH are functions of the irrigation water, equipment, composition of the precipitate, temperature, and type and concentration of the acid. An acid concentration that maintains a pH of 5.5 to 7.0 will control precipitates. The periodic injection of an acid treatment should reduce the cost of controlling bicarbonates. Another way to reduce this cost is to aerate the irrigation water and keep it in a reservoir until equilibrium is reached and the precipitates have settled out.

Sodium hypochlorite should be used to treat hard ground-water supplies. Treatment with calcium hypochlorite causes calcium to precipitate.

Iron precipitation at the emitter can be prevented by deliberately precipitating the iron and filtering it out before it enters the pipe network. A chemical feeder can be set to provide a measured amount of chlorine solution to oxidize the iron and other organic compounds present and to allow a chlorine residue, for example 1 ppm.

Chelating the iron with a phosphate chelating agent at two to five times the concentration of the iron molecules should eliminate the problem. If concentrations are as high as 10 ppm, however, aeration by a mechanical aerator and settling in a reservoir may be more practical. Mechanical injection of air into the water supply followed by filtration is another method of removing iron.

Oxidation and reduction reactions are the usual means of cleaning iron bacteria from trickle systems. Normally, the system is superchlorinated (i.e., rate of at least 10 ppm) to oxidize the organic material and clear the irrigation system. Continuous injection of chlorine, however, is believed to be the best method of combating iron bacteria.

Both algae and slime can be controlled by chlorination, which is inexpensive, efficient, and effective. Typical recommended chlorine dosages are as follows:

1. For algae use 0.5 to 1.0 ppm continuously or 20 ppm for 20 min in each irrigation cycle.
2. For iron bacteria use 1 ppm more than the parts per million of iron present. (This can vary depending on the amount of bacteria to control.)
3. For iron precipitation use 0.64 × the ferrous ion content.
4. For manganese precipitation use 1.3 × the manganese content.
5. For slime maintain 1 ppm free residual chlorine at ends of laterals.

The efficiency of chlorine treatment is related to the pH of the water to be treated: the higher the pH, the more chlorine required. In treating severe cases of algae and slime, an algae detention/destruction chamber is used; it usually consists of a large pond or concrete chamber to retain the chlorine-treated irrigation water long enough to destroy the algae and slime.

System Components

A trickle irrigation system consists of the control head, main and submain lines, manifold, laterals, emitters, flow controls, and flow/pressure regulators (fig. 7–5).

Control Head

The control head includes the pumping station, water-measuring devices, fertilizer and chemical injection equipment, valves, and filtering equipment.

Pumping Station

The pumping station consists of the power unit (internal combustion engine or electric motor) and a centrifugal, deep-well, or submersible pump and appurtenances. In the design and selection of pumping equipment for a trickle irrigation system, high efficiency is the principal requirement.

Water-Measuring Devices

A key requirement of operating a trickle system is knowing how much water is being supplied. In-line flowmeters may register total flow in standard volumetric units: gallons, cubic feet, acre-feet, miner's inch-days, or others. Some flowmeters turn off automatically when a certain amount of water has been applied.

Fertilizer and Chemical Injection Equipment

Injectors may be used to apply fertilizer or other chemicals directly into the trickle irrigation system. Methods of injection are:

Suction.—Suction of chemicals through the intake side of a pump is a simple injection method; however, corrosive materials may cause excessive wear on pump parts. Furthermore, it is difficult to monitor accurately the rate of input as the chemical level in the supply tank lowers.

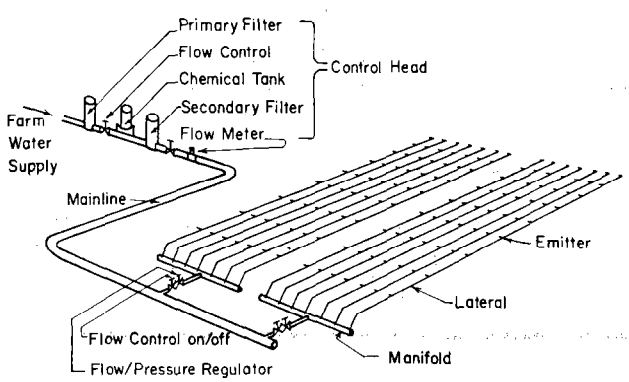


Figure 7–5.—Basic components of a trickle irrigation system.

Pumping.—Pumping is the most versatile method for injecting chemicals into trickle irrigation systems. Positive-displacement piston pumps can be designed and calibrated to give an accurate low or high injection rate, but they must be properly maintained. The pump draws the fertilizer solution from an open tank and injects it by positive displacement into the irrigation line. Water-driven fertilizer pumps use the pressurized water from the irrigation line to drive the pump by means of diaphragms or pistons that have a larger surface area than the injection piston. Thus, the pump injects chemicals at a higher pressure than the pressure of the water that drives it. The small amount of water that drives the pump (two to three times the volume of fertilizer injected) is expelled.

On engine-driven pumping plants, the fertilizer injector pump can be driven by a belt-and-pulley arrangement. On electric installations, the fertilizer pump can be driven with a fractional-horsepower electric motor. Both engine- and electric-driven pumps are usually less expensive and have fewer moving parts to be maintained than water-driven pumps. Automatic volumetric shutoff valves are available for water-driven pumps and automatic time controllers are available for electric-driven pumps. Injection can be stopped by letting the chemical tank run dry, but this practice may damage the injector pump unless it is shut off.

Differential pressure.—Differential pressure also can be used to inject chemicals into the irrigation water. In a differential pressure system, the chemical tank is under the same pressure as the main line. Venturi pipe sections can be used to create a significant pressure loss. The Venturi effect is obtained by narrowing the inlet pipe diameter and then gradually expanding it back to the inlet diameter size. The Venturi throat pressure is lower than the pipeline pressure because of the higher velocity through the throat. Most of the pressure is regained in the expansion section, however, which makes the Venturi tube a very efficient differential pressure device. Figure 7–6 shows the components of a Venturi-tube-type pressure-differential injection system.

Pressure-differential injection systems have no moving parts, require no external power source, and are less expensive than pump injectors. Their main

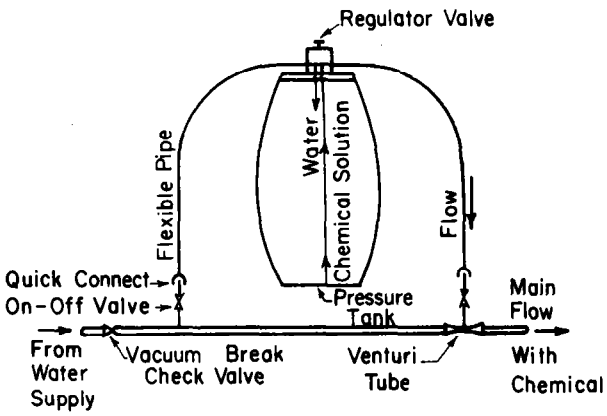


Figure 7-6.—Pressure-differential injection system.

disadvantage is that the chemical solution to be injected must be contained in a tank at the same pressure as that in the main line (instead of in a lightweight tank open to the atmosphere). Because large, noncorrosive, high-pressure tanks are expensive, small tanks are usually used, even though more labor is required for more frequent servicing.

Valves

Valving needed at the head depends upon the method of operating the trickle irrigation system. Figure 7-7 shows valving for a system with fertilizer and chemical injection, control valves, and safety controls.

The components shown are:

(1) Start valve
(2) Automatic valve (operating according to the volume of discharge)
(3) Nonreturn valve
(4) Air valve
(5) Connections to and from the fertilizer tank
(6) Valve for regulating the nutrient solution flow
(7) Filter
(8) Pressure gage
(9) Connection for measuring pressure behind the filter
(10) Fertilizer tank

Sediment Removal

Filtering to remove from the water debris that might clog or otherwise foul the emitters or sprayers is essential on most systems. Central filtration enables more convenient and efficient control of water cleanliness than does filtration at small segments of the system.

The type of filter needed depends on the contaminant. Contaminants can be classified into two general groups, physical and chemical. The physical contaminants are suspended solids including organic and inorganic components. Algae, bacteria, diatoms, larvae, fish, snails, and seeds and other plant parts are the major organic contaminants. The inorganic

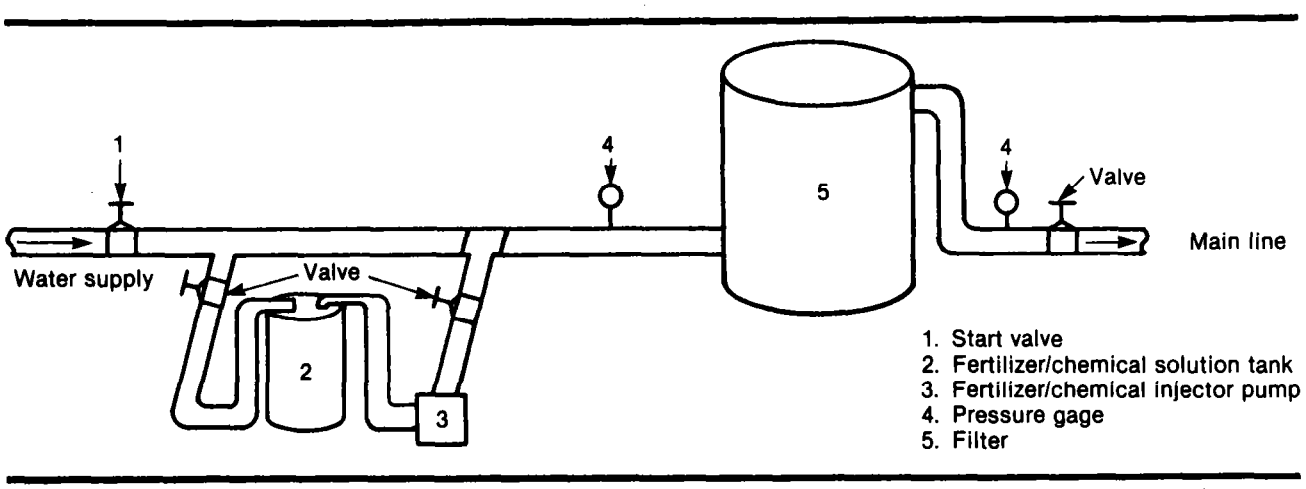


Figure 7-7.—Valves at the head of a trickle irrigation system.

contaminants are mainly in the basic range of soil particles. The chemical contaminants are solutes that precipitate and become potential blocking agents. They are also sources of food for slime bacteria that can cause pipe and emitter clogging.

Evaporation may leave the dissolved solids on the outside of emitters to cause plugging if the opening is not protected by the equipment design or installation method. Furthermore, precipitates and slimes can restrict flow and eventually block the distribution pipe, tubing, and emitters. Removing unwanted chemicals requires processes such as reverse osmosis or ion exchange, which is generally not economically feasible. But injecting certain chemicals into the irrigation water to neutralize the adverse effects of unwanted chemicals has proved economical.

Consistency of the water quality must be considered, and filtration and treatment must be planned for the average worst condition. Open water such as lakes, ponds, rivers, streams, and canals can vary widely in quality and often contains large amounts of organic matter and silt. Warm weather, light, and slow-moving or still water favor rapid algal growth. Open waters often require use of a prefilter, such as a settling basin or vortex separator, followed by a sand filter and then a screen filter. In some instances chemical coagulants are required to control silt and chlorine is needed to control algae.

Municipal or domestic water comes from various sources, such as reservoirs and wells, and undergoes various levels of treatment. Wells usually have good-quality water, but they can deliver small to large quantities of sand. The water may also be chemically unstable and produce chemical precipitates in the pipes and emitters.

Adequate filtration requires processing all the water entering the system. The particle size of the contaminants that can be tolerated depends on the emitter construction and should be indicated by the manufacturer or known from local experience. Removal of particles 10 or more times smaller than the emitter opening is recommended because several particles may group together and bridge the emitter openings. This behavior is typical for organic particles having about the same density as water. Also, inorganic particles heavier than water, such as fine and very fine sands, tend to settle out and deposit in the slow-flow section of pipe near the ends of laterals and when the system is turned off. Fine sand particles also tend to settle along the inside of laminar-flow emitters in which the flow rate is zero along the walls even during operation. The resulting clogging may not be rapid, but it is inevitable.

Filtering equipment.—Screen filters, if adaptable, are the simplest, least expensive, and most efficient means for filtering water. Gravel and graded sand filters consist of fine gravel and sand of selected sizes placed inside a cylindrical tank to filter out heavy loads of very fine sand and organic matter. Vortex sand separators depend on centrifugal force to remove and eject high-density particles from the water. Although vortex devices do not remove organic materials, they are efficient for ejecting large quantities of very fine sand or larger inorganic solids before their further infiltration through screens.

Settling pools.—Settling basins, ponds, or reservoirs can be used to remove large volumes of sand and silt. However, sedimentation alone will not provide the desired water quality. In fact, algal growth and windblown contaminants in the pool may cause more filtration problems than sediment. Therefore, open water areas should be avoided if possible, particularly if the water supply is from a well. After the water is drawn from the pool, it must be chemically treated and filtered through various combinations of filters and screens.

For settling pools to be effective, the intake to the trickle system should be located so that water from the upper level of the pool enters the system. The pool should be sized to limit turbulence and permit a minimum of 15 min for water to travel from the pool inlet to the system intake. A minimum of 15 min is required for most inorganic particles larger than 80 microns (about #200 sieve) to settle. Where possible, the pool should be long and narrow. If construction area is limited, baffles or U-shape construction will be needed. Example: To provide settle time for a 2-ft^3/s flow, a pool should be 45 ft long, 10 ft wide, and 4 ft deep. Control of vegetation and algal growth in the pool may require lining the sides and bottom of the pool to control vegetation and frequent chemical treatment to control algae.

Screen filters.—In screen filters, the hole size and the total amount of open area determine the efficiency and operational limits.

The basic parts of a screen filter are the filter screen and basket. The screen is stainless steel, nylon, or polyester mesh. Moderate amounts of algae tend to block the screen quickly unless the screen filter is specifically designed to accommodate an organic contaminant.

A blow-down filter uses either stainless steel mesh, which offers relative strength, or nylon mesh arranged so that water can be flushed over the surface without disassembling the filter. Nylon mesh has the advantage of fluttering during a flushing cycle, so that the collected material is broken up and expelled. A back-flushing filter allows the flow of water through the screen to be reversed; the collected particles are taken with the water. Gravity-flow filters function by running the water onto a large mesh screen, letting gravity pull it through, and then picking it up with a pump and delivering it to the distribution points. Some gravity-flow filters have sweeping spray devices under the screen to lift the contaminants and move them to one side and away.

A screen filter should be cleaned when the pressure head loss is about 3 to 5 psi or at a fixed time determined in advance. The most common methods of cleaning are (1) manual cleaning, i.e., pulling out the filter basket and cleaning it by washing; (2) cleaning by repeated washing, i.e., washing the filter basket by backflushing or otherwise washing (blowing off) the basket without dismantling the filter; and (3) automatic cleaning, which takes place during the filter operation continuously, on a time schedule, or whenever the pressure loss across the filter reaches a certain level.

Regardless of the cleaning method, extreme caution should be taken to prevent dirt from bypassing the filter during cleaning. Backflushing with precleaned water is recommended. Downstream filters, such as a small filter or hose washer screen at each lateral connection, provide an additional factor of safety. Extreme caution in keeping large dirt particles out of the system is necessary and is especially important during accidents such as main-line breaks. A small amount of sand or organic particles large enough to clog the tricklers could ruin them.

The head loss in a clean filter normally ranges between 2 and 5 psi, depending on the valving, filter size, percentage of open area in the screen (sum of the holes), and discharge. In designing the system, the anticipated head loss between the inlet and outlet of the filter just before cleaning should be taken into consideration. This total head loss ranges between 5 and 10 psi.

A screen filter can handle a wide range of discharges, but a filter with a high discharge in relation to its screen area requires frequent cleaning and may have a short life. When estimating the appropriate discharge for a given screen filter, consider the quality of water, filtration area and percentage of open area, desired volume of water between cleaning cycles, and allowable pressure drop in the filter surface.

Typical maximum recommended flow rates for fine screens are less than 200 gpm/ft^2 of screen open area. The wire or nylon mesh takes up much of the screen area. For example, a standard 200-mesh stainless steel screen has only 58 percent open area. An equivalent nylon mesh with the same size openings has only 24 percent open area. Therefore, ideal flow rates should range from 40 to 100 gpm/ft^2 of total screen area, depending on the percentage of open area.

Sand media filters.—Graded sand filters consist of fine gravel and sand of selected sizes inside a cylindrical tank. As the water passes through the tank, the gravel and sand filter out heavy loads of very fine sands and organic material. Gravel filters are often constructed so that they can be backwashed automatically as needed. A recommended practice is to use a screen filter downstream from the gravel filter unless the gravel filter has its own backup screen device to pick up any particles that might escape during backwashing.

Sand media filters are most effective for organic material, because they can collect large quantities of such contaminants before backwashing is necessary. Also, if the predominant contaminant is long and narrow, such as some algae or diatoms, the particle is more likely to be caught in the multilayered sand bed than on a single screen surface.

Factors that affect the characteristics and performance of sand filters are water quality, types and size of sand media, flow rate, and allowable pressure drop. Although they are more expensive than comparable screen filters, sand filters can handle larger loads with less frequent backflushing and a smaller pressure drop. Sand filters are recommended when a screen filter would require frequent cleaning or when particles to be removed are smaller than the 200-mesh opening.

The sand media used in most trickle-irrigation-system filters are designated by numbers. Numbers 8 and 11 are crushed granite, and numbers 16, 20, and 30 are silica sands. The mean granule size is about 1,900, 1,000, 825, 550, and 340 microns for numbers 8, 11, 16, 20, and 30, respectively.

At a flow velocity of 25 gpm/ft^2 through the sand bed, numbers 8 and 11 crushed granite remove

most particles larger than one-twelfth of the mean granule size or larger than about 160 and 80 microns, respectively. The sand numbers 16, 20, and 30 remove particles larger than about one-fifteenth the mean granule size or larger than about 60, 40, and 20 microns, respectively.

It is common practice to select the smallest medium possible for a given installation; however, a larger medium may sometimes be desirable. The larger medium generally causes less pressure drop and has a slower buildup of particles. In many gravity systems, the pressure drop is critical, and the larger medium not only has a lower pressure drop when clean, but also needs less frequent flushing for a given allowable increase in pressure drop.

Typically, the initial pressure drop across numbers 8, 10, and 16 media is between 2 and 3 psi, and for numbers 20 and 30 media it is about 5 psi. The rate of pressure drop increase tends to be linear with time. The relative rates of pressure drop increase, based on an arbitrary 1 unit of pressure drop per unit of time for number 11 medium are: 0.2 for number 8, 2 for number 16, 8 for number 20, and 15 for number 30. For example, if it takes 15 hr for the pressure drop to increase by 5 psi across a number 11 medium, the same water would be expected to cause a 5-psi increase in about 2 hr across a number 20 medium.

In practice, the maximum recommended pressure drop across a sand filter is generally about 10 psi. Backflushing must be frequent enough to hold the pressure drop within the prescribed design limits. If backflushing is required more than twice daily, automatic backflushing is recommended. Automatic backflushing can be activated by a timer or by a switch that senses the pressure differential across the medium.

Backflushing flow rates vary with the size of the medium and the construction of the filter. Typical required backflushing flow rates for free-flow filters range from 10 to 15 gpm/ft² of bed for numbers 30 and 20 media and between 20 and 25 gpm/ft² of bed for numbers 16 and 11 media.

The flow rate across the medium is an important consideration in filter selection. Present-day high-rate filter technology is based on a nominal value of 20 gpm/ft² of bed; this value has been established relative to a given bed composition and filter use. For trickle irrigation, however, the level of filtration required may be such that rates about 30 gpm/ft² may be allowed.

Figure 7–8 shows the effect of flow rate on the maximum particle size passing through a typical filter with media of various sizes. For a given quality of water and size of filter medium, the size of particles passing through increases with the flow rate.

Vortex sand separators.—Modern vortex (centrifugal) sand separators can remove up to 98 percent of the sand particles that would be removed by a 200-mesh screen. The vortex separators depend on centrifugal force to remove and eject high-density particles from the water. They cannot remove organic materials.

Although vortex separators do not remove all the required particles, they are efficient for ejecting large quantities of very fine sand, such as that from a well that is bringing up sand. The separator should always be backed by a screen filter downstream to catch contaminants that may pass through, especially during startup and shutdown.

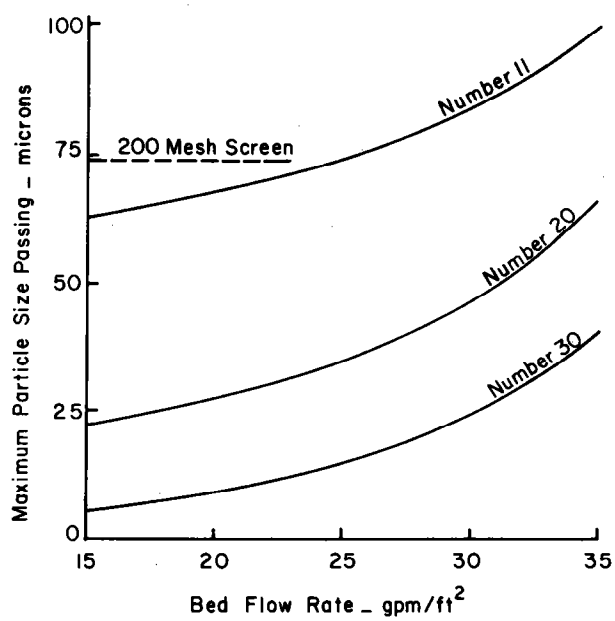


Figure 7–8.—Effect of flow rate on the maximum particle size passing through a typical free-flow sand filter with media of various sizes.

Main and Submain Lines

The main and submain lines carry water from the control head to the manifold or directly to the lateral lines. The basic system subunit includes the manifold with attached laterals. Pressure control or adjustment points are provided at the inlets to the manifold. Because of these pressure-control-point locations, pipe size selection for the main and submain lines is not affected by the pressure variation allowed for the subunit. Therefore, the pipe size should be selected based primarily on the economic tradeoff between power costs and pipe installation costs. Design and installation of the main and submain lines should be in accordance with the *National Handbook of Conservation Practices.*[1]

As with other irrigation pipelines, the flow velocity, check valves, air and vacuum relief valves, and pressure relief valves must be considered and incorporated as part of the system. A means of flushing and draining the pipelines also should be incorporated into the main line and submain system.

Manifolds

The manifold, or header, connects the main line to the laterals. It may be on the surface, but usually it is buried.

The limit for manifold pressure loss depends on the topography, pressure loss in laterals, and total pressure variation allowed for the emitter chosen. Once these limits have been established, standard calculations for hydraulic pipelines with multiple outlets may be used.

On flat terrain, the connection from submain or main line to manifold is in the center of the manifold. If there is any appreciable slope, the downhill elevation gain can be balanced by reducing the pipe size or by moving the connection point uphill to increase the number of laterals served downhill. Typically, a combination of both means is used to balance the downhill elevation gain. An uphill pressure loss can be balanced by reducing the number of uphill laterals served, increasing the size of the manifold piping, or both.

Frequently, the manifold connection to the main line is the point at which in-field pressure is regulated. It is also the point at which flow control can be automated; valves or other devices can turn the water to this subunit on and off. On steep fields, one pressure-regulating point cannot serve more than one lateral; in such cases, several pressure- or flow-regulating points may be needed. One regulating point may serve two to five laterals (fig. 7–9) or one may be required at each lateral.

Laterals

In trickle irrigation systems, the lateral lines are the pipes on which the emitters are attached. Water flows from the manifold into the laterals, which are usually made of plastic tubing ranging from 3/8 to 1 in. in diameter. Continuous-size tubing provides better flushing.

The layout of lateral lines should be such that it provides the required emission points for the crop to be irrigated. Sometimes two laterals per row of trees are needed. Other methods of obtaining more emission points per tree are zigzag and "snake" layouts and use of pigtail lines looped around or between the trees. The use of "spaghetti" tubing to provide multioutlet emission points is another way to distribute water. Figure 7–10 shows various lateral layouts for widely spaced permanent crops.

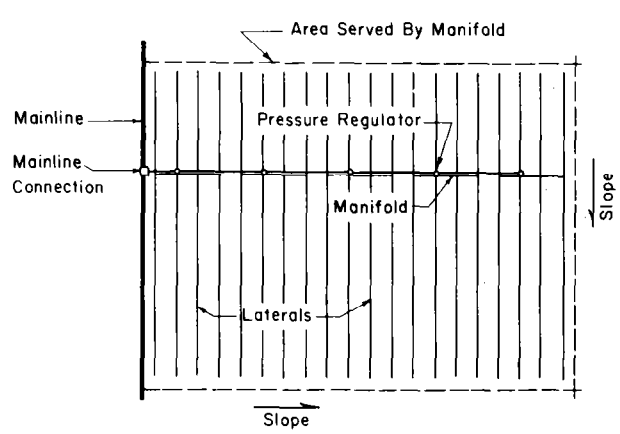
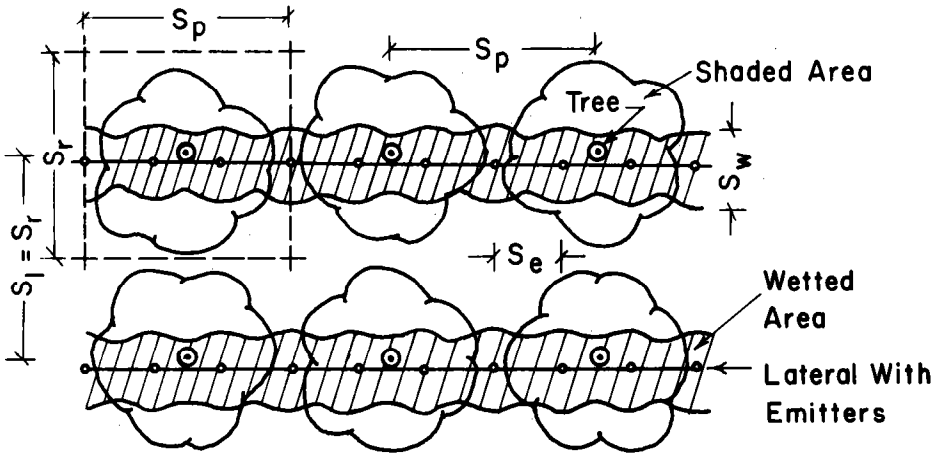
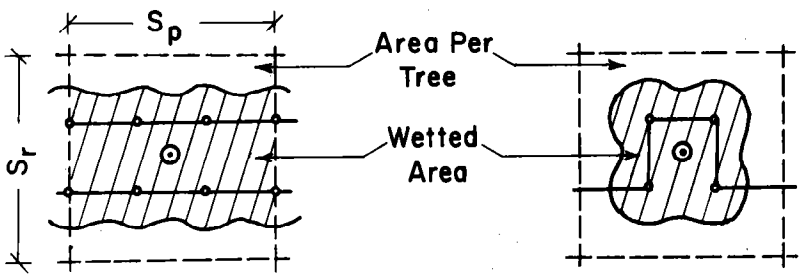


Figure 7–9.—Manifold layout showing inlet connection uphill from center and showing pressure-regulated manifolds.

[1]Soil Conservation Service. 1977–80. National Handbook of Conservation Practices. U.S. Dep. Agric. Unnumbered.

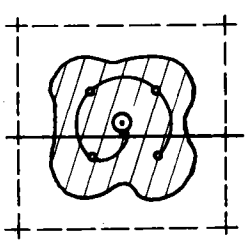


A. Single lateral for each tree row. S_p = plant spacing; S_r = row spacing; S_w = width of wetted strip; S_e = emitter spacing; S_l = lateral spacing.

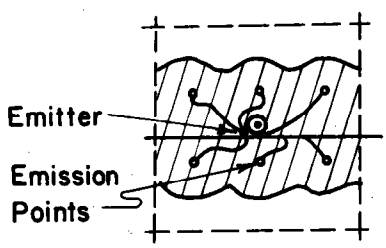


B. Double laterals for each tree row.

C. Zigzag lateral for each tree row.



D. Pigtail with four emitters per tree.



E. Multiexit six-outlet emitter with distribution tubing.

Figure 7-10.—Various lateral layouts for a widely spaced permanent crop.

Definitions of terms used in figure 7–10 are as follows:

P_s = percent area shaded—the average horizontal area shaded at midday by the crop canopy as a percentage of the total crop area.

P_w = percent area wetted—the average horizontal area wetted in the top part of the crop root zone as a percentage of the total crop area.

S_e = emitter spacing—the spacing between emitters or emission points along a lateral, feet.

S_l = lateral spacing, feet.

S_p = plant spacing in the row, feet.

S_r = row spacing, feet.

S_w = width of the wetted strip, feet.

Emitters

In drip, subsurface, or bubbler irrigation, emitters are used to dissipate pressure and discharge water. An emitter permits a small uniform flow or trickle of water at a constant discharge that does not vary significantly with minor differences in pressure head. Ideally, emitters should have either a relatively large flow cross section or some means of flushing to reduce clogging. Emitters should be both inexpensive and compact.

The point on or beneath the ground at which water is discharged from an emitter is called the emission point. Trickle irrigation with water discharged from emission points that are individually and widely spaced—usually more than 3 ft—is called point-source application.

Because of various conditions affecting trickle irrigation, an assortment of emitters has been developed. To dissipate pressure, long-path emitters use a long capillary-size tube or channel, orifice emitters use a series of openings, and vortex emitters use a vortex effect. Flushing emitters use a flushing flow of water to clear the discharge opening each time the system is operated. Continuous-flushing emitters continuously permit the passage of large solid particles while discharging a trickle or drip flow. This type of emitter can reduce filtering requirements. Compensating emitters discharge water at a constant rate over a wide range of lateral line pressures. Multioutlet emitters supply water to two or more points through small-diameter auxiliary tubing. Figures 7–11 through 7–16 show construction and characteristics of emitters.

Emitters are located at predetermined spacing on the lateral and are connected by various means (fig. 7–17).

Other types of water applicators used in trickle irrigation are line-source tubing and sprayers. Trickle irrigation with water discharged from closely spaced perforations or a porous wall along the lateral line is called line-source application.

Three types of line-source tubing are used in line-source application. Single-chamber tubing is a small-diameter hose with punched openings spaced 2 ft or less apart. Double-chamber tubing is a small-diameter hose with a main and an auxiliary bore separated by a single wall. The double-chamber tubing has widely spaced inner openings punched in the separator wall between the main and auxiliary bores. For each inner opening, three to six exit holes are punched at 0.5- to 2-ft intervals in the outer wall of the auxiliary bore. Porous-wall tubing is a small-diameter hose with a uniformly porous wall. The pores are of capillary size and ooze water when under pressure.

Aerosol emitters, foggers, spitters, misters, or miniature sprinklers are used in spray irrigation. These devices dissipate pressure and discharge a small uniform spray of water to cover an area of 10 to 100 ft^2. Sprayers should have a low water trajectory and a single large flow cross section, and should apply the water evenly.

Flow Controls and Pressure Regulators

Because trickle irrigation is used to obtain high irrigation efficiencies, flow- and pressure-control devices are an integral part of the system. Flow and pressure must be controlled during each phase of the irrigation—namely, setting and operation of the equipment, water application, and water distribution—by hand-operated pressure controls and on-off valves, sequential operation, or partial or full automation. Each of the methods requires a cycling process. Table 7–1 shows the characteristics of various cycling methods.

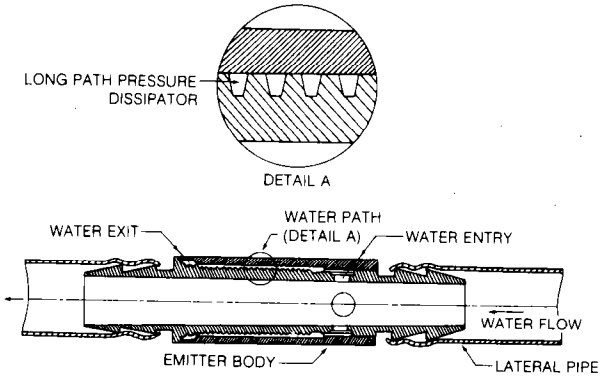


Figure 7–11.—Single-exit long-path emitter.

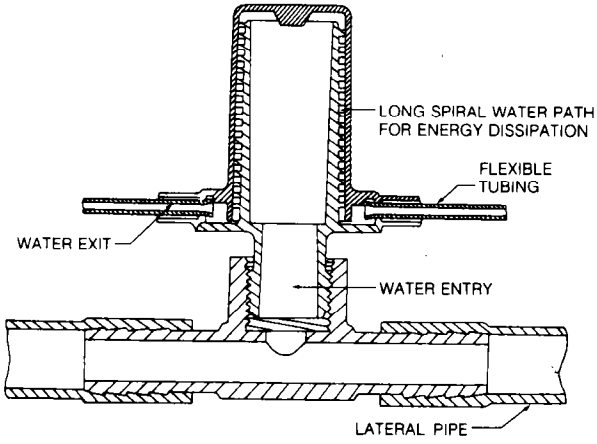


Figure 7–12.—Multiexit long-path emitter.

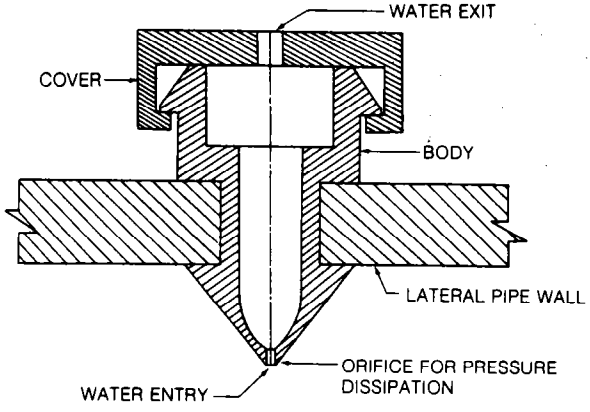


Figure 7–13.—Single-exit orifice-type emitter.

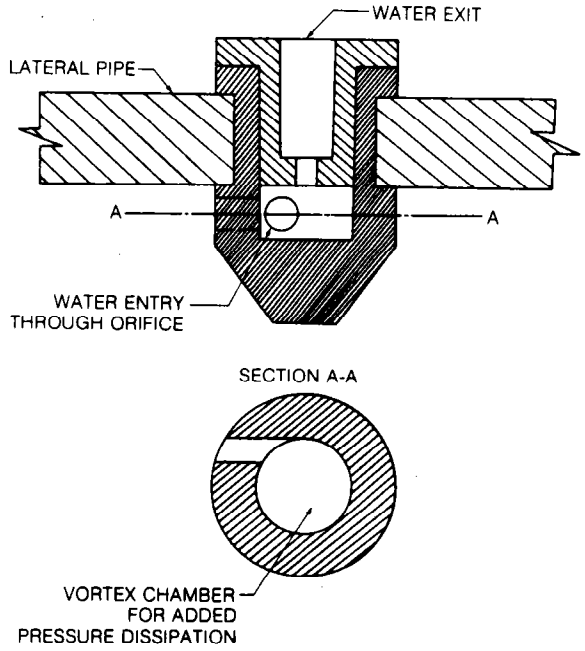


Figure 7–14.—Orifice-vortex-type emitter.

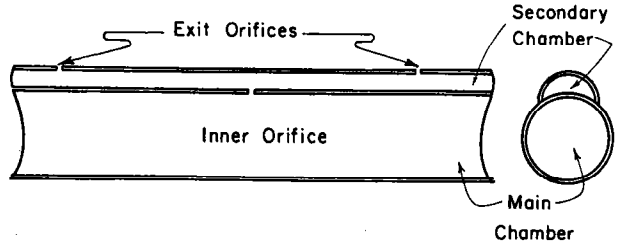
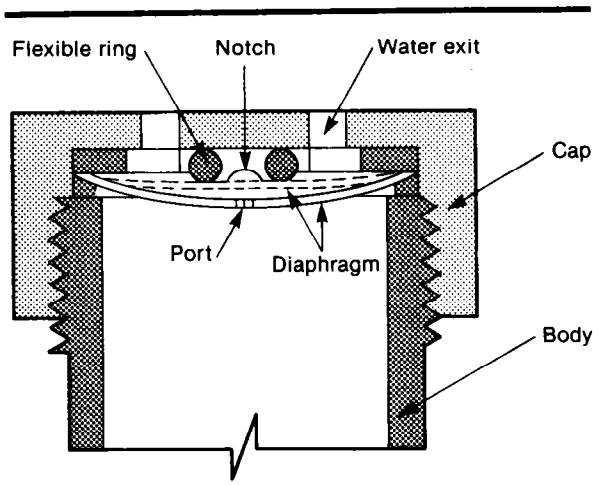


Figure 7–15.—Twin-wall emitter lateral.



Note: diaphragm is shown in relaxed position—dotted line shows diaphragm in operating position

Figure 7-16.—Flushing-type emitter.

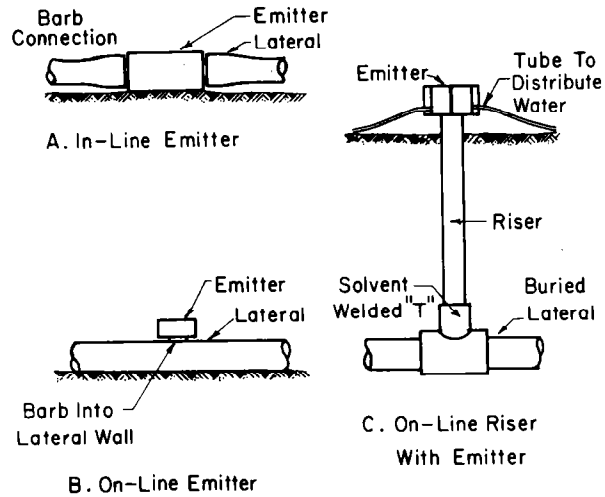


Figure 7-17.—Typical means for connecting emitters to laterals.

Table 7-1.—Cycling method characteristics of a trickle irrigation system

Cycling method	Beginning of irrigation cycle	Basis for closing valve	Manner of opening next valve	Order of valve operation	To change irrigation depth	To change the order of operation
Hand valve	Manual opening	Time	Manual	Without restrictions	Change on-time or pressure	Without limitations
Volumetric valve	Manual opening	Quantity of water	Manual	Without restrictions	Manually adjust valve	Without limitations
Sequential operation with volumetric valve	Manual opening	Quantity of water	Hydraulic control	Adjoining areas; from low to high areas	Manually adjust valve	Possible only by relocating the control lines
Full automation by time or volume	Automatic, planned in advance	Time or volume	Hydraulic or electric control lines	Without restrictions	Adjust time or volume	Resetting at the control board
Full automation by soil moisture	Automatic, according to soil moisture	Soil moisture level	Automatic; independent of other valves	Order in which soil dries	Adjust soil moisture sensors	Without any prescribed order

Hand-Operated Pressure Controls and On-Off Valves

The flow rate is controlled by adjusting the pressure with manual valves set to balance flow rates among the subunits of the system. It is important to check and adjust the valves to keep emitter discharges uniform.

Another method of flow control is the use of pressure or flow regulators at the inlet to each lateral or header feeding a small group of laterals. These valves are usually preset for a given pressure or flow rate and often cannot be adjusted or reset. These valves must be incorporated into the system design and not installed as an afterthought, because only a limited selection of pressures or flow rates is available with the small, low-cost valves.

Jumper tubes of various diameters and lengths can be used to connect each lateral to the manifold. The tubes can be cut to the length that provides the pressure loss required to produce uniform lateral inlet pressures along a manifold with nonuniform pressures. In effect, the jumper tubes serve as fixed precision fluid resistors, and the uniformity of pressure that can be achieved is limited only by practical design and installation considerations.

Sequential Operation

Parts of the system can be operated sequentially with volumetric control valves that are interconnected by hydraulic control lines. As each valve closes, the next valve opens. When the sequencing operation is completed, the valves must be readjusted, and the first valve must be activated manually to start the cycle again. It is also desirable (essential in steep areas) to plan the irrigation so that valve activation proceeds from lower to higher plots.

Partial Automation

Volume control is well suited to trickle irrigation. Volume can be controlled most simply with some automation by use of volumetric or mechanical timeclock valves. Semiautomatic volumetric control valves can be placed at the head of each subunit, or a single such valve can be used at the control head along with ordinary valves controlling each subunit. The volumetric valve requires manual opening and adjustment, but it closes automatically. The use of volumetric valves does not dictate a special operating sequence. Because the amount of water applied is measured, precise pressure control is not required at the inlets to volumetric valves. Pressure control is required if mechanical timeclock valves are used.

Full Automation

Operation can be fully automated either by using a central controller operated on a time or volume basis or by soil-moisture sensing.

Automation on a time or volume basis requires a control system operating either hydraulic or electric valves. The controller automates the irrigation for an unlimited number of cycles. The order in which the valves operate can be altered from one cycle to the next. Both the operating time of each valve and the quantity of water distributed can be changed easily at the control panel. Rather than using a fixed-cycle interval for the system, the cycle of each irrigation can be started by a sensor in a National Weather Service class "A" evaporation pan or its equivalent, or by weather instruments.

Soil moisture sensors in the plant root zone can be used to activate the controller to open and close the valves. It is customary to use a tensiometer as the moisture sensor. The tensiometer measures the soil moisture tension and signals the valve controlling each subunit, and the valve opens or closes. Because each valve operates automatically and is not connected to any other valve, the order of operation is not dictated in advance. Therefore, the circuitry must pass through some type of control panel to eliminate the simultaneous opening of more than the desired number of valves. Trickle systems automatically controlled by soil moisture are not in wide use because of the technical problems associated with the uneven distribution of microlevel moisture.

Operation and Maintenance

The manner of operating and maintaining all components determines the success or failure of any trickle irrigation system.

Operating a trickle system involves the following steps for the owner-operator:

1. Acquiring complete information and instructions from the designer and dealer.
2. Determining when and how long to irrigate.
3. Checking the water meter readings and recording the figures.
4. Accurately setting the hydraulic metering valve.
5. Operating the head valve to begin irrigation.
6. Checking the system along all components for proper operation, beginning with pressure readings at the header.
7. Checking the emitters, at least on a random basis.
8. Setting the chemical and fertilizer injection equipment.

Reliable performance of a trickle system depends on preventive maintenance that includes proper filtration, pipe flushing, and field checks of mechanical devices.

The various methods of cleaning filters are discussed earlier in this chapter. Normally the filter is designed with 20 to 30 percent extra capacity. Unless the filter has an automatic backflushing system, it must be hand cleaned daily during the irrigation.

After construction or repairs, the system should be flushed systematically, beginning with the main line and proceeding to the submains, manifolds, and laterals. The main lines and then the submains should be flushed one at a time with the manifold or riser valves turned off. Closing the valves on all lines except the one being flushed allows a large flow of water. The manifolds should be flushed with all the lateral riser valves turned off. Finally, the lateral hoses should be connected and flushed for about an hour on each operating station.

Fine sand, silt, and clay tend to settle in the low-velocity section of the system, at the ends of manifolds and laterals. Emitters receiving high concentrations of these fine contaminants are susceptible to clogging; therefore, periodic flushing is a recommended part of a good maintenance program. Annual flushing is enough for many systems, but some water and emitter combinations require almost daily flushing to control clogging. If frequent flushing is required, automatic and semiautomatic flushing valves are recommended at the ends of the laterals. A water velocity of about 1.0 ft/s is required to flush fine particles from lateral tubing. For ½-in.-diameter tubing this is about 1.0 gpm.

Systematic checking is required to spot malfunctioning emitters. Slow clogging causing partial blockage results from sediments, precipitates, organic deposits, or mixtures of these. Physical deterioration of parts is a concern with pressure-compensating emitters. The flow passage may slowly close as the compensating part wears out. Mechanical malfunction can also be a problem in flushing emitters.

Emitters should be cleaned, replaced, or repaired when emission uniformity (EU) drops 5 to 10 percent below the design uniformity or when the average emitter discharge (q_a) times EU/100 is insufficient to satisfy the plants' requirements for water. The cleaning required depends on the emitter and the problem. Some emitters can be disassembled and cleaned manually. Others can be manipulated and flushed to get rid of loose deposits. Carbonate deposits can be removed by injecting 0.5- to 1-percent acid solution at manifold or lateral inlets. With this treatment, a contact time of 5 to 15 min in the emitters will normally suffice. Sulfuric acid should be used for iron precipitates. Acid treatment may not be practical or 100 percent effective and obviously is ineffective for completely clogged emitters.

Air pressure of 5 to 10 atm applied at lateral inlets can remove jellylike deposits from long-tube emitters. The emitters and connections to the lateral hose, however, must be very strong to withstand the pressure, and the method is not effective for all types of clogging or on all emitters. The use of high water pressure to clean emitters is limited because getting enough pressure to the end emitters is virtually impossible.

Pipeline, valves, and pumps require little maintenance. Normal precautions should be taken for drainage at winter shutdown and for filling in spring. Before spring startup and during the irrigation season, components should be lubricated according to the manufacturer's recommendations.

Trickle irrigation systems are designed and managed to deliver light, frequent applications of water that wet only a section of the soil. The irrigation procedures given in Chapter 1, Soil-Plant-Water Relationships, National Engineering Handbook, Section 15, must be adjusted for trickle application. Under conventional flood and sprinkler water application, the irrigation needs for depth, frequency, and salinity controls are based on maximum moisture storage in the root zone. However, to meet the objective of trickle irrigation, water application is based on moisture replacement in a small area of the soil. This requires determining the wetted area, wetting pattern, and vertical and horizontal water movement in the soil. The values of water requirements, consumptive use, and frequency of irrigation are adjusted accordingly.

Area Wetted

The area wetted (A_w) used in trickle irrigation lies along a horizontal plane about a foot below the soil surface. Because of variation in texture, structure, slope, and horizontal layering of a soil, a mathematical relationship to determine A_w may not be precise.

Table 7–2 gives estimates of A_w at a depth of about 6 to 12 in. in various soils. The table values are based on a common emitter flow rate of 1.0 gph for daily or every-other-day irrigations; the rate of application slightly exceeds the rate of consumptive use. The estimated A_w is given as a rectangle with the wetted width (S_w) equal to the maximum expected diameter of the wetted circle and the optimum emitter spacing (S_e') equal to 80 percent of that diameter. This emitter spacing gives a reasonably uniform and continuous wetted strip. Multiplying S_w by S_e' gives about the same area as that of a circular wetted area.

The most reliable way to determine A_w is to conduct field tests in which test emitters are operated at a few representative sites in a field and the wetting pattern is checked. The flow rate and volume of water applied in a test should be similar to the design values expected for the system under consideration.

The following equipment is needed to make a field test:

1. A 20- to 30-gallon container.
2. A 4-foot stand for the container.
3. A 10-foot piece of ¼- or ⅜-in.-diameter tubing to attach to the bottom of the container.

Table 7–2.—Estimates of area wetted (A_w)[1] in various soils

Soil or root depth and soil texture[3]	Kind of soil layers[2]		
	Homogeneous	Varying layers, generally low density	Varying layers, generally medium density[4]
	$S_e' \times S_w = A_w$ (ft²)	$S_e' \times S_w = A_w$ (ft²)	$S_e' \times S_w = A_w$ (ft²)
Depth 2.5 ft			
Coarse	1.2 × 1.5 = 1.8	2.0 × 2.5 = 5.0	2.8 × 3.5 = 9.8
Medium	2.4 × 3.0 = 7.2	3.2 × 4.0 = 12.8	4.0 × 5.0 = 20.0
fine	2.8 × 3.5 = 9.8	4.0 × 5.0 = 20.0	4.8 × 6.0 = 28.8
Depth 5 ft			
Coarse	2.0 × 2.5 = 5	3.6 × 4.5 = 16.2	4.8 × 6.0 = 28.8
Medium	3.2 × 4.0 = 12.8	5.6 × 7.0 = 39.2	7.2 × 9.0 = 64.8
Fine	4.0 × 5.0 = 20.0	5.2 × 6.5 = 33.8	6.4 × 8.0 = 51.2

[1]Based on an emitter flow rate of 1.0 gph. The estimated A_w is given as a rectangle with the wetted width (S_w) equal to the maximum expected diameter of the wetted circle and the optimum emitter spacing (S_e') equal to 80 percent of that diameter.

[2]Most soils are layered. As used here, "varying layers of low density" refers to relatively uniform texture but with some particle orientation, some compaction layering, or both that gives higher horizontal than vertical permeability; "varying layers of medium density" refers to changes in texture with depth as well as particle orientation and moderate compaction.

[3]"Coarse" includes coarse to medium sands, "medium" includes loamy sands to loams, and "fine" includes sandy clay loam to clays (if clays are cracked, treat as coarse to medium soils).

[4]For soils with varying layers and high density, the A_w may be larger than the values shown.

4. A turbulent-flow emitter with a discharge rate about equal to the expected design flow rate.
5. A 100-ml graduated cylinder.
6. A watch with a second hand.
7. A shovel and soil auger.

The test is performed as follows:

1. Place the container on the stand, and calibrate the test emitter by measuring its discharge when the water level in the container ranges from 7 to 4½ ft.
2. Position the test emitter.
3. Fill the container with the amount of water required to provide the expected design daily flow for an emitter.
4. Release the daily flow requirement through the test emitter. If the soil is very dry, wait 2 or 3 days before checking the wetting pattern.
5. Dig a trench 12 to 18 in. deep through the test emitter location.
6. Measure the width and depth of wetting at 6-in. intervals from the test emitter.
7. Plot the cross section and compute the wetted area.

Figure 7–18 shows the wetting patterns for about 12 gal of water applied to dry sandy soil at rates of 1, 2, and 4 gph. The sandy, clay-textured desert soil was dry before the test. Note that the vertical and horizontal wetting patterns are similar for the three rates with equal volumes of water applied.

The 1-gph emitter produced a wider wetted area than the emitters with higher flow rates, which is unusual. The 4-gph emitter did not cause ponding and the 1-gph emitter provided more time for horizontal water movement. With repeated wettings, as in an irrigation program, the area wetted would probably be larger for the higher flow rates.

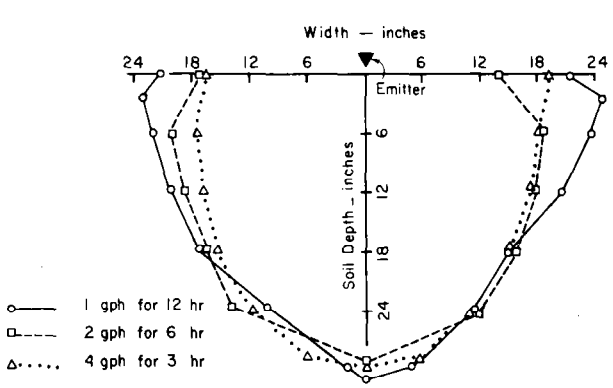


Figure 7–18.—Wetting pattern profiles for equal volumes (12 gal) of water applied at three rates to a dry sandy soil.

Figure 7–19 shows the relationship between the maximum horizontal and vertical movement in a uniform sandy soil for various water-application rates. The data points in the figure further demonstrate that, in uniform soils, the volume of soil wetted depends on the amount of water applied and is relatively independent of the application rate. Figure 7–19 shows that if too much water is applied, the water could easily move past the root zone depth. Light, daily applications minimize deep percolation losses but wet a smaller area.

Spray emitters wet a relatively large area of soil. They are often used instead of drip emitters on coarse-textured homogeneous soils on which many drip emitters would be required to wet a sufficient area.

Figure 7–20 shows the comparison between wetting patterns and areas wetted under drip and spray emitters. Water moves out laterally from the wetted surface area under a spray emitter.

Most soils have layers of various densities, textures, or both. However, assuming large values for A_w without making field tests as described earlier is risky. With many differences in the texture and high density of the soil layers, the A_w may be twice as large as the values given for a layered soil in table 7–2 but this can only be determined by actual field checks. Table 7–2 should be used only for estimation. Values of A_w greater than those given for uniform texture and low-density conditions should

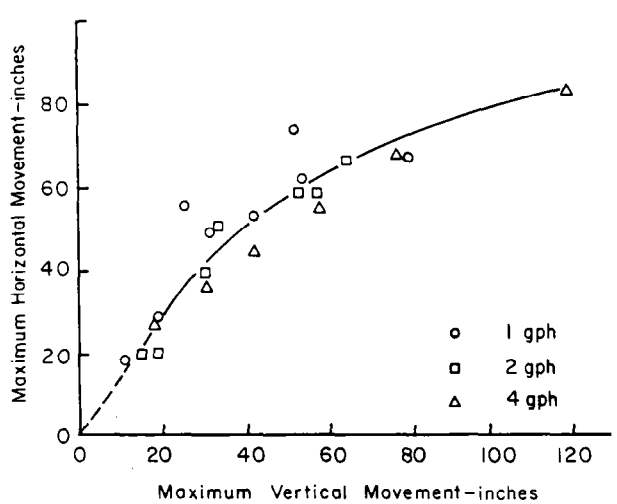


Figure 7–19.—Relationship between vertical and horizontal water movement in a dry sandy soil for various amounts of water and various application rates.

be used with caution until they are checked in the field.

On sloping fields the wetting pattern distorts in favor of the downslope direction. On steep fields this distortion can be extreme, with as much as 90 percent of the pattern on the downslope side. The actual area wetted will be similar to that on flat ground but the distortion should be considered in the placement of emission points.

Percent Area Wetted

The percent area wetted (P_w) is the average horizontal area wetted in the top 6 to 12 in. of the root zone as a percentage of the total crop area.

For a trickle system with straight laterals of single drip emitters and emitter spacing (S_e) equal to or less than optimum emitter spacing (S_e'), the P_w can be computed by equation 7–1.

$$P_w = \frac{eS_eS_w}{S_pS_r} \times 100 \qquad \textbf{(7–1)}$$

Where

- e = number of emission points per plant.
- S_e = spacing between emitters on a lateral, feet.
- S_w = width of the strip that would be wetted by emitters on a lateral at S_e' or closer, feet.
- S_p = plant spacing in the row, feet.
- S_r = plant row spacing, feet.

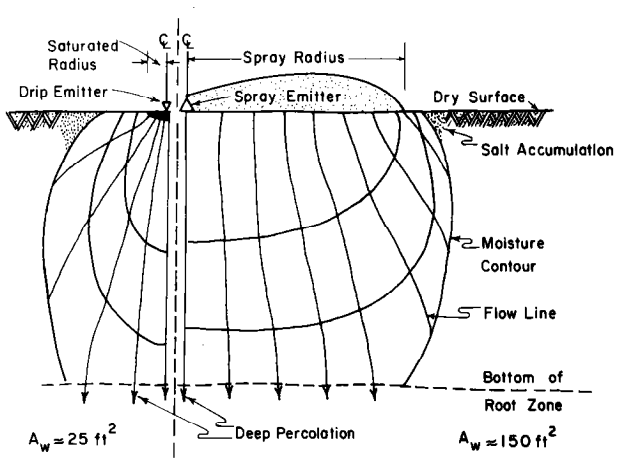


Figure 7–20.—Idealized wetting patterns in a homogeneous fine sandy soil under a drip and a spray emitter.

For trickle systems with straight laterals of single drip emitters where S_e is greater than the optimum emitter spacing (S_e') (80 percent of the wetted diameter, feet), S_e in equation 7–1 must be replaced by S_e'.

For trickle systems with double laterals or zigzag, pigtail, or multiexit layout, the P_w can be computed by equation 7–2.

$$P_w = \frac{eS_e'(S_e' + S_w)}{2(S_pS_r)} \times 100 \qquad \textbf{(7–2)}$$

For double laterals, the two laterals should be placed apart at a distance equal to S_e'. This spacing gives the greatest A_w and leaves no extensive dry areas between the double lateral lines. For the greatest A_w with zigzag, pigtail, and multiexit layouts, the emission points should be placed at a distance equal to S_e' in each direction.

If the layout is not designed for maximum wetting and $S_e < S_e'$, then S_e' in equation 7–2 should be replaced by S_e.

For a trickle system with spray emitters, P_w can be computed by equation 7–3.

$$P_w = \frac{e[A_s + (\tfrac{1}{2}S_e' \times PS)]}{(S_pS_r)} \times 100 \qquad \textbf{(7–3)}$$

Where

- A_s = estimate of the soil surface area wetted per sprayer from field tests with a few sprayers, square feet.
- PS = perimeter of the area directly wetted by the test sprayers, feet.
- $\tfrac{1}{2}S_e'$ = one-half the S_e' values for homogeneous soils (table 7–2), feet.

No single right or proper minimum value for the P_w of various soils has been determined. However, systems designed with high P_w values provide more stored water and are easier to schedule. For widely spaced crops such as vines, bushes, and trees, a reasonable design objective is to wet at least one-third and up to one-half of the horizontal cross-sectional area of the root system. In areas that receive supplemental rainfall, designs that wet less than one-third of the horizontal cross-sectional area of the root system may be adequate for medium- and heavy-textured soils. Wetting should be kept below 50 or 60 percent in widely spaced crops to keep the surface area between rows relatively dry for cultural

practices and reduce evaporation losses. Capital costs of a system increase with the size of the P_w, so the smaller P_w is favored for economic reasons. In crops with rows spaced less than 6 ft apart, the P_w usually approaches 100 percent.

Figure 7–21 shows the relationship that may exist between potential production and P_w for systems providing full plant water requirements. Currently data are too few to enable plotting specific curves for potential crop production vs. P_w. It is reasonable to assume in plotting figure 7–21 that the curves should start near zero for areas that have little or no rainfall and that production would increase rapidly with small increases in P_w. It is also reasonable to assume that production will peak before 100 percent of the area is wetted. Figure 7–21 should be used cautiously because crop-soil-climate systems may vary widely.

Meeting Irrigation Water Requirements

The concept of management-allowed deficit, the amount of plant canopies, the average peak daily transpiration rate, and the application efficiency of the low quarter of the area are considered in determining the depth or quantity of water to be applied at each irrigation and the frequency of irrigation.

The management-allowed deficit (M_{ad}) is the desired soil-moisture deficit (S_{md}) at the time of irrigation; the S_{md} is the difference between field capacity and the actual moisture available at any given time. The M_{ad} is expressed as a percentage of the available moisture-holding capacity of the soil or as the corresponding S_{md} related to the desired soil moisture stress for the crop-soil-water-weather system. Irrigation by sprinkler or flood systems is normally carried out when the S_{md} equals the M_{ad}. With trickle irrigation the S_{md} is allowed to become much more severe before irrigation. In arid areas, an irrigation usually replaces the S_{md}. In humid areas, however, an irrigation may replace less than 100 percent of the S_{md} to leave soil capacity for storing moisture from rainfall.

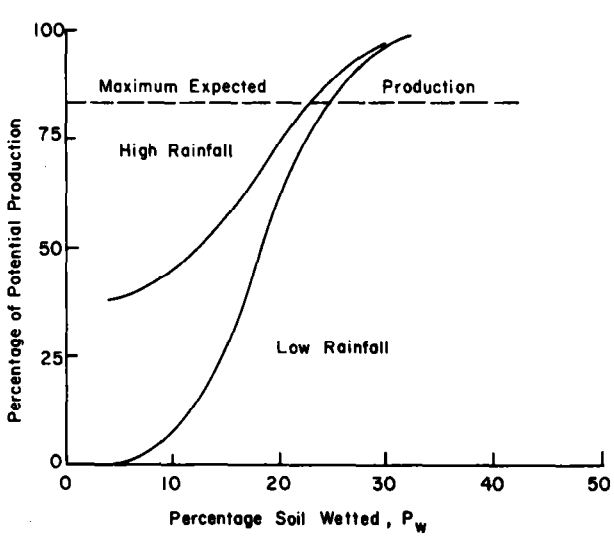


Figure 7–21.—Hypothetical relation of potential production to percent area wetted.

Plant canopy is the area of land surface shaded, in which the vegetation intercepts radiation rays.

Average peak daily transpiration rate is a function of the monthly consumptive use rates.

The application efficiency of the low quarter (E_{lq}) is the ratio of the average low-quarter depth of irrigation water infiltrated and stored in the root zone, or required for leaching, to the average depth of irrigation water applied. The average low-quarter depth infiltrated is the average of the lowest one-fourth of measured or estimated values each representing an equal area of the field. When the average low-quarter depth of irrigation water infiltrated is equal to or less than the S_{md} plus leaching requirements, and minor losses are negligible, the E_{lq} is equal to the field uniformity coefficient. The average seasonal E_{lq} is the seasonal irrigation efficiency.

Maximum Net Depth of Application

The maximum net depth of application (F_{mn}) is the depth of water needed to replace the soil moisture deficit (S_{md}) when it is equal to the management-allowed deficit (M_{ad}). The F_{mn} is computed as a depth over the whole crop area and not just the area wetted (A_w) as previously discussed.

The F_{mn} for trickle irrigation can be computed by equation 7–4.

$$F_{mn} = (M_{ad})(WHC)(RZD)(P_w) \qquad (7\text{–}4)$$

Where

M_{ad} = percentage of management-allowed deficit.
WHC = water-holding capacity of the soil, inches per foot.
RZD = depth of the soil occupied by plant roots, feet.
P_w = percent area wetted.

Consumptive Use Rate

Under trickle irrigation, nonbeneficial use of water is reduced to a minimum. Transpiration by the crop plants accounts for practically all the water consumed. The consumptive use estimates developed from procedures in *Irrigation Water Requirements*[2] require modification for trickle irrigation design. The modification is expressed in terms of average peak daily transpiration rate (T_d), inches per day, for the month of greatest water use. The relationship of T_d to modified consumptive use values from *Irrigation Water Requirements* for trickle irrigation is expressed in equation 7–5.

$$T_d = u_d[P_s + 0.15(1.0 - P_s)] \qquad \textbf{(7–5)}$$

Where

u_d = average daily consumptive-use rate for the month of greatest overall water use, inches per day.

P_s = percent area shaded.

The P_s can be estimated after determining the land area covered by the plant or tree canopy. Equation 7–5 has not been thoroughly verified by field research; however, it is based on a logical analysis coupled with field observations and some field testing.

Seasonal Transpiration

The seasonal transpiration rate (T_s), inches per year, can be computed by replacing u_d in equation 7–5 with the total crop consumptive use (U), inches.

Net Depth of Application

The net depth of application (F_n), inches, for trickle irrigation systems is the net amount of moisture to be replaced at each irrigation to meet the consumptive use requirements. Normally F_n is less than or equal to the maximum net depth of application (F_{mn}). If less than F_{mn} is applied per irrigation, then F_n can be computed by equation 7–6.

$$F_n = T_d I_f \qquad \textbf{(7–6)}$$

Where

T_d = average peak daily transpiration rate for the mature crop, inches per day.

I_f = maximum allowable irrigation interval, days.

Gross Water Application

The gross amount of water to be applied at each irrigation, (F_g), inches, includes sufficient water to compensate for the system nonuniformity and unavoidable losses, and to provide for leaching. Taken into consideration in F_g are the peak-use-period transpiration ratio (T_r), the emission uniformity, and the leaching requirement ratio. The T_r is the ratio of the average peak daily transpiration rate (T_d) to the total water applied. Values of T_r to compensate for unavoidable deep percolation losses are:

1. T_r is equal to 1 for crops with roots deeper than 5 ft in all soils except very porous gravelly soils; for crops with root zones between 2.5 and 5 ft deep in fine- and medium-textured soils; and for crops with root zones less than 2.5 ft deep in fine-textured soils.
2. T_r is equal to 1.05 for crops with deep root zones in gravelly soils; for crops with medium root zones in coarse-textured (sandy) soils; and for crops with shallow root zones in medium-textured soils.
3. T_r is equal to 1.10 for crops with medium root zones in gravelly soils and for crops with shallow root zones in coarse-textured soils.

The design emission uniformity (EU) is an estimate of the percentage of the average depth of application required by a system to irrigate adequately the least watered plants. The EU can be computed by equation 7–7.

$$EU = 100\left(1.01 - \frac{1.27}{\sqrt{e}}v\right)\frac{q_n}{q_a} \qquad \textbf{(7–7)}$$

Where

EU = design emission uniformity, percent.

e = number of emitters per plant (≥ 1).

v = manufacturer's coefficient of variation.

q_n = minimum emitter discharge computed with the minimum pressure using the nominal relationship between emitter discharge and pressure head, gallons per hour.

q_a = average emitter discharge (of all the

[2]Soil Conservation Service. 1967. Irrigation Water Requirements. U.S. Dep. Agric. Soil. Cons. Service., Technical Release 21.

emitters under consideration), gallons per hour.

The leaching requirement ratio (LR_t) will be discussed later.

The F_g can be computed by equation 7–8a and 7–8b. When $T_r \geq 1/(1.0-LR_t)$ or $LR_t \geq 0.1$, the F_g can be computed by equation 7–8a.

$$F_g = \frac{F_n T_r}{EU} \qquad \textbf{(7–8a)}$$

When $T_r < 1/(1.0 - LR_t)$ and $LR_t > 0.1$, the F_g can be computed by equation 7–8b.

$$F_g = \frac{F_n}{EU(1.0 - LR_t)} \qquad \textbf{(7–8b)}$$

Where

F_n = net depth of application, inches.

The gross volume of water required per plant per day [$F_{(gp/d)}$] is a value used in the design of emitter flow rate; $F_{(gp/d)}$, in gallons per day, can be computed by equation 7–9.

$$F_{(gp/d)} = 0.623 \frac{S_p S_r F_g}{I_f} \qquad \textbf{(7–9)}$$

Where

S_p = plant spacing, feet.
S_r = plant row spacing, feet.
I_f = maximum allowable irrigation interval, days.

The annual net depth of application [$F_{(an)}$], inches, to meet consumptive use requirements may be reduced by the effective rainfall during the growing season (R_e), inches, and residual stored soil moisture from off-season precipitation (W_s), inches. The values R_e and W_s are subtracted from seasonal consumptive use requirements.

The F_{an} for trickle irrigation can be computed by equation 7–10.

$$F_{(an)} = (U - R_e - W_s)[P_s + 0.15(1.0 - P_s)] \qquad \textbf{(7–10)}$$

Where

U = seasonal total crop consumptive use, inches.
P_s = percent area shaded.

In using $F_{(an)}$ to make an economic analysis of pumping costs, mean values for R_e and W_s should be used. In determining irrigation water storage, probability of less rainfall should be analyzed.

Seasonal Irrigation Efficiency

The seasonal transpiration (T_s) and seasonal irrigation efficiency (E_s), percent, values are needed to determine requirements for seasonal irrigation-water supplies and pumping.

The E_s is a function of application uniformity; losses from runoff, leaks, line flushing, and drainage; unavoidable deep percolation losses caused by wetting pattern and untimely rainfall; and losses resulting from poor irrigation scheduling.

When the seasonal transpiration ratio (T_R) $\leq 1/(1.0 - LR_t)$, E_s can be computed by equation 7–11.

$$E_s = EU \qquad \textbf{(7–11)}$$

When $T_R > 1/(1.0 - LR_t)$ to satisfy the leaching requirement, E_s can be computed by equation 7–12.

$$E_s = \frac{EU}{T_R(1.0 - LR_t)} \qquad \textbf{(7–12)}$$

Where

LR_t = leaching requirement ratio.
EU = emission uniformity, percent.

The T_R represents the minimum excess amount of water that must be applied to offset unavoidable deep percolation losses. Such losses are due to untimely rains, leakage from the soil, or both while enough water is moving horizontally. With good system design and scheduling, use the T_R values given in table 7–3. The higher T_R values given for humid areas account for untimely rainfall.

Gross Seasonal Depth of Application

The gross seasonal depth of application (F_{sg}), inches, can be computed by equation 7–13.

$$F_{sg} = \frac{F_{an}}{E_s(1.0 - LR_t)} \quad (7\text{–}13)$$

Where

F_{an} = annual net depth of application, inches.
E_s = seasonal irrigation efficiency, percent.
LR_t = leaching requirement ratio.

Gross Seasonal Volume

The gross seasonal volume (V_i), acre-feet, of irrigation water required for an acreage under a trickle system can be computed by equation 7–14.

$$V_i = \frac{F_{an}A}{12(1.0 - LR_t)E_s/100} \quad (7\text{–}14)$$

Where

F_{an} = annual net depth of application, inches.
A = area under the system, acres.
E_s = seasonal irrigation efficiency, percent.
LR_t = leaching requirement ratio.

Plant Response

Plant response is about the same to trickle irrigation as to other methods of irrigation. Even mature orchards that have been irrigated by sprinkle or surface irrigation methods can be converted to trickle irrigation. The root systems of most trees can adapt to the smaller wetted area in a few months. Thus, the conversion should be made just before or during the low use or dormant season; the tree's root system will then have time to adapt with little shock before the peak use period. Conversely, conversions made during the peak use period can severely stress a mature orchard. In very young orchards conversions can be made at any time.

If there is enough precipitation to wet the soil a few feet deep, plant roots will extend beyond the trickle-irrigated area. This root activity is important; it may account for a significant amount of the water and nutrient uptake. There is little evidence that root anchorage is a problem under trickle irrigation where $P_w \geq 33$ percent, but in high wind areas, any root extension that resulted from natural precipitation would be helpful.

Optimum Moisture Levels

Optimum moisture levels are easily maintained with a well-designed trickle irrigation system. Even without automation, daily irrigations are done almost as easily as weekly irrigations. Therefore, systems are often run daily, every other day, or twice weekly depending on crop needs and agronomic practices. Under frequent irrigation, the plant roots undergo little shock or stress from irrigation. The roots can seek and remain in a constant favorable environment.

It is important to wet a relatively large part of the potential root system to ensure some degree of safety (moisture reserve) in case of temporary system failure. It is also important to have a large enough volume of moist soil to promote root extension and water uptake.

Table 7–3.—Seasonal transpiration ratios for arid and humid regions with various soil textures and rooting depths

Climate zone and root depth	T_R[1] for indicated soil texture			
	Very coarse	Coarse	Medium	Fine
Arid				
<2.5 ft	1.15	1.10	1.05	1.05
2.5 to 5.0 ft	1.10	1.10	1.05	1.00
>5.0 ft	1.05	1.05	1.00	1.00
Humid				
<2.5 ft	1.35	1.25	1.15	1.10
2.5 to 5.0 ft	1.25	1.20	1.10	1.05
>5.0 ft	1.20	1.10	1.05	1.00

[1]Seasonal transpiration ratios (T_R) are for drip emitters. For spray emitters add 0.05 to T_R in humid climates and 0.10 in arid climates.

Salinity Control

All irrigation water contains some dissolved salts, which are usually pushed toward the fringes of the wetted soil mass during the irrigation season. By applying more water than the plants consume, most of the salts can be pushed or leached below the root zone, but it is impossible to avoid having some areas of salt accumulation.

The most critical zones of accumulation are along the fringes of the wetted surface (fig. 7–20). A light rain can leach these accumulated salts down into the zone of extensive root activity and thereby severely injure plants. This hazard can be minimized by operating the trickle system during any rainy period to wash the salts down and out of the root zone.

If rainfall is less than 6 to 10 in. per year, supplemental applications by sprinkler or surface irrigation may be necessary to prevent critical levels of salt buildup. Supplemental applications are especially important where irrigation water is saline or where annual crops may be planted in the salty fringe areas of previous years' wetted patterns.

Crop Tolerance and Yield

Trickle irrigation affords a convenient and efficient method of frequent irrigation that does not wet the plant leaves. Applying frequent light irrigations keeps the salt concentration in the soil water to a minimum. Daily applications and sufficient leaching keep the salt concentrations in the soil water at almost the same level as that in the irrigation water because there is little drying between irrigations, and therefore the salts remain diluted. When irrigations are infrequent, the salts become more concentrated as the soil dries.

With good-quality water, yields with trickle irrigation should be equal to or slightly better than those with other methods under comparable conditions. With poor-quality water, yields may be better with trickle irrigation because of the continuous high moisture content and daily replenishment of water lost by evapotranspiration. Frequent sprinkler irrigation might give similar results, but saline water causes leaf burn and defoliation of sensitive plants.

Salts that accumulate below the emitters can be flushed down continuously by irrigations properly applied daily or every other day. If the leaching requirement ratio (LR_t) is more than 0.1, the daily irrigations should include enough extra water to maintain a slight but nearly continuous downward movement of water to control the salts.

Knowledge of the electrical conductivity of the irrigation water (EC_w), mmhos per centimeter, and the electrical conductivity of the saturated soil extract (EC_e), mmhos per centimeter, is useful in determining crop tolerance to an irrigation water. The minimum (min) and maximum (max) EC_e are useful in estimating leaching requirements under trickle irrigation. The min EC_e is the maximum concentration of salinity at which yields are unimpaired. The max EC_e is the theoretical level of salinity that would reduce yield to zero; i.e., if the entire root zone were at this salinity, the plants would not extract water, and growth would stop. Table 7–4 gives values for min and max EC_e for various crops. These values were extrapolated from test data that gave 0-, 10-, 25-, and 50-percent reductions in yield.

The theoretical reduction in yield (Y), percent, for various crops that is caused by salinity in the trickle irrigation water when $EC_w >$ min EC_e can be estimated by equation 7–15.

$$Y = \frac{EC_w - \min EC_e}{\max EC_e - \min EC_e} \times 100 \qquad \textbf{(7–15)}$$

For high-frequency irrigation, if $EC_w \leq$ min EC_e, Y will be zero.

Leaching Requirement

Harmful soluble salts must be removed from the crop root zone in irrigated soils if high crop production is to be sustained.

In arid regions where salinity is a major problem, additional irrigation water must be applied for leaching. In determining the requirements for trickle irrigation to supply leaching water, the leaching requirement ratio (LR_t), the ratio of the equivalent depth of the drainage water to the depth of irrigation water, is used. Most of the natural precipitation available has been accounted for in average annual effective rainfall (R_e) for meeting average consumptive use. Therefore, in arid areas very little of the R_e helps satisfy the leaching requirement. Furthermore, because only a part of the soil area is wetted and needs leaching under trickle irrigation, the effects of R_e in determining LR_t can almost always be neglected, and LR_t can then be computed by equation 7–16.

Table 7–4.—Minimum (min) and maximum (max) values of EC_e for various crops[1]

Crop	EC_e (mmhos/cm) Min	Max	Crop	EC_e (mmhos/cm) Min	Max
Field crops					
Barley	8.0	28	Corn	1.7	10
Cotton	7.7	27	Flax	1.7	10
Sugarbeet	7.0	24	Broadbean	1.6	12
Wheat	6.0	20	Cowpea	1.3	8.5
Sorghum	4.0	18	Bean	1.0	6.5
Fruit and nut crops					
Date palm	4.0	32	Apricot	1.6	6
Fig, olive	2.7	14	Grape	1.5	12
Pomegranate	2.7	14	Almond	1.5	7
Grapefruit	1.8	8	Plum	1.5	7
Orange	1.7	8	Blackberry	1.5	6
Lemon	1.7	8	Boysenberry	1.5	6
Apple, pear	1.7	8	Avocado	1.3	6
Walnut	1.7	8	Raspberry	1.0	5.5
Peach	1.7	6.5	Strawberry	1.0	4
Vegetable crops					
Beets	4.0	15	Sweet corn	1.7	10
Broccoli	2.8	13.5	Sweet potato	1.5	10.5
Tomato	2.5	12.5	Pepper	1.5	8.5
Cucumber	2.5	10	Lettuce	1.3	9
Cantaloupe	2.2	16	Radish	1.2	9
Spinach	2.0	15	Onion	1.2	7.5
Cabbage	1.8	12	Carrot	1.0	8
Potato	1.7	10	Bean	1.0	6.5

[1]Taken from Ayers, R.S., and D.W. Westcot. 1976. Water Quality for Agriculture. U.N. Food and Agric. Org. Irrigation and Drainage Paper 29.

Note: Min EC_e does not reduce yield; max EC_e eliminates yield.

$$LR_t = \frac{L_n}{F_n} = \frac{L_N}{F_{an}} = \frac{EC_w}{EC_{dw}} \quad (7\text{–}16)$$

Where

L_n = net leaching requirement for net application per irrigation, inches.
F_n = net depth of application, inches.
L_N = annual leaching requirement for net seasonal application, inches.
F_{an} = annual net depth of application, inches.
EC_w = electrical conductivity of the irrigation water, mmhos per centimeter.
EC_{dw} = electrical conductivity of the drainage effluent, mmhos per centimeter.

Equation 7–16 is based on a steady salt balance or, in popular terminology, "what goes in must come out, and nothing comes from in between." It is important to understand the meaning of the value calculated for LR_t. It represents the minimum amount of water (in terms of a fraction of the applied water) that must pass through the root zone to prevent salt buildup. The actual LR_t, however, can be determined only by monitoring soil salinity.

The LR_t for high-frequency, daily, or alternate-day irrigation can be computed by equation 7–17.

$$LR_t = \frac{EC_w}{2(\max EC_e)} \quad (7\text{–}17)$$

Where

EC_e = electrical conductivity of the saturated soil extract, mmhos per centimeter.

Once F_n or F_{an} is determined, the total net water requirement may be computed by $F_n/(1.0 - LR_t)$ or $F_{an}/(1.0 - LR_t)$.

The calculated LR_t should be adequate to control salts unless they already exceed the crop's tolerance. If they do, an initial heavy leaching, preferably by sprinkle or surface irrigation, may be needed.

A step-by-step procedure is normally followed in designing a trickle irrigation system. In trickle irrigation, water is carried in a pipe network to the points where it infiltrates the soil. The primary objective of good trickle-irrigation-system design is to irrigate adequately the least-watered plant. Uniformity of application depends on the uniformity of emitter discharge. Nonuniform discharge is caused by pressure differences resulting from friction loss and elevation, by emitter variation within manufacturing tolerances, and by clogging.

Design Criteria

Emitters dissipate the pressure in the pipe distribution network as the water flows from the lateral hoses into the atmosphere. The pressure is dissipated by small-diameter orifices, a series of orifices, vortex chambers, short tubes, long tubes, or tortuous flow paths. A general knowledge of the emitter design theory for the various pressure-dissipation methods helps in selecting an emitter design.

Some important design criteria that affect efficiency and performance of trickle systems are:

1. Efficiency of filtration.
2. Permitted variations of pressure head.
3. Base operating pressure used.
4. Degree of flow or pressure control used.
5. Relationship between discharge and pressure at the pump or hydrant supplying the system.
6. Allowance for temperature correlation for long-path emitters.
7. Chemical treatment to dissolve mineral deposits.
8. Use of secondary safety screening.
9. Incorporation of flow monitoring.
10. Allowance for reserve system capacity or pressure to compensate for reduced flow from clogging.

A checklist of procedures in designing a trickle irrigation system follows. Some of the steps are discussed in other chapters of Section 15, Irrigation, National Engineering Handbook, or in earlier sections of this chapter.

1. Inventory available resources and operating conditions. Include information on soils, topography, water supply, power source, crops, and farm operation schedules following instructions in Chapter 3, Planning Farm Irrigation Systems.
2. Determine water requirement to be met with

a trickle system, as discussed in Soil-Plant-Water Considerations in this chapter.

3. Determine appropriate type of trickle system.
4. Select and design emitters.
5. Determine capacity requirements of the system.
6. Determine required sizes of main-line pipe, manifold, and lateral lines.
7. Check pipe sizes for power economy.
8. Determine maximum and minimum operating conditions.
9. Select pump and power unit for maximum operating efficiency within the range of operating conditions.
10. Determine appropriate filter system for site conditions.
11. Determine requirements for chemical fertilizer equipment.
12. Plan field evaluation.
13. Prepare drawings, specifications, cost estimates, schedules, and instructions for proper layout, operation, and maintenance.

Emitter Selection Criteria

Selecting emitters requires a combination of objective and subjective deduction.

Emitter design and selection procedures require an assessment of discharge, spacing, and the type of emitter to be used. This process is one of the most critical factors in the design of a trickle irrigation system. It is not simply a matter of following a checklist of instructions; it requires the designer to reason because the various decisions required are interrelated.

System efficiency depends on the emitter selection and the design criteria. Some emitter characteristics that affect efficiency are:

1. Discharge rate variations caused by emitter variation within manufacturing tolerances.
2. Closeness of discharge-pressure relationship to design specifications.
3. Emitter discharge exponent.
4. Possible range of suitable operating pressures.
5. Pressure loss on lateral lines caused by the connection of emitters to the lateral.
6. Susceptibility to clogging, siltation, or buildup of chemical deposit.
7. Stability of discharge-pressure relationship over a long period.

The choice of emitters depends not only on emitter physical characteristics, but also on emitter placement, type of operation, diameter of laterals, and user preference. Selection requires four steps: (1) evaluate and choose the general type of emitter that best meets the need in the area to be wetted; (2) choose the specific emitter needed to meet the required discharge, spacing, and other planning considerations; (3) determine the average emitter discharge (q_a) and pressure-head (h_a) requirements; and (4) determine the allowable subunit pressure-head variation ($\triangle H_s$) for the desired emission uniformity (EU).

The two most important items in emitter selection are the percent area wetted (P_w) and the emitter reliability (resistance to clogging and malfunctioning). The greater the P_w, the longer the system can be down or an emitter can be plugged before the plants become excessively stressed.

Initially, emitter selection depends on the soil, plant water requirement, emitter discharge, water quality, and terrain of a particular location. The choice of a particular emitter should follow a detailed evaluation that includes emitter cost and system risks. Generally, the emitters offering the more desirable features and lower system risks have a higher unit cost. Also to be evaluated is the effect a particular emitter will have on the cost of the main line and filtration system.

A reasonable design objective is to have enough emission points to wet at least one-third and up to one-half of the potential horizontal cross section of the potential root system. There is some interaction between the emitter discharge rate and area wetted per emission point; but the density of emission points required to obtain $P_w \geq 33$ percent can usually be based on a 1-gph emitter discharge rate by using the procedures described under Area Wetted.

The water required for plant growth increases until the plant reaches its peak-use growth stage. Lower initial installation costs and water savings can be achieved by installing the number of emitters required for each stage of growth. The initial pipe network, however, must be designed to meet the needs of the mature plant. Operating the system with less than the ultimate number of emitters usually affects the uniformity of application. The best choice is a balance between (1) higher installation costs and lower water-use efficiency and (2) lower installation costs, higher water-use effi-

ciency, and added installation costs at a later date.

Ideally, emitters should (1) be long lasting and inexpensive; (2) discharge at a relatively low rate that does not vary significantly between emitters because of variation within manufacturing tolerances, expected differences in pressure head resulting from friction loss and elevation, or expected changes in temperature; and (3) have relatively large passageways or be self-flushing to reduce clogging. These goals are not easily met in the design of an emitter because they are contradictory to a certain extent.

General Suitability

General emitter suitability means how well the emitter fits into the particular design and matches the size and water requirements of the crop. Emission devices are available that will emit water at individual point locations or along the length of a line. The point source devices come with single or multiple outlets. With more than one outlet, distribution tubing is generally used to deliver the water from the emitter to the desired discharge location.

Single-outlet emitters can be used to water small individual areas or can be arranged around larger plants to provide dual- or multiple-outlet emission points. Dual-outlet emitters are often used on vines, and multiple-outlet emitters are generally used in orchards, where each tree may require several emission points.

The cost of emitters is not proportional to the number of outlets. For instance, a dual-outlet emitter is probably more expensive than an otherwise comparable single-outlet emitter but less expensive than two single-outlet emitters. Thus, emitters with more outlets are generally less expensive per outlet.

For row crops such as strawberries or vegetables, line-source tubing fits well with the cropping pattern because it provides the linear wetted strip desired. Cost is especially important in row-crop trickle irrigation because the density of the crop requires a large amount of line-source tubing. Emitters also can provide linear wetted strips for row crops.

As well as fitting in with the intended cropping pattern, the emitting system chosen must be able to deliver the right flow rate at the right pressure. Because there are so many emission points within a field, even a small difference between the actual and desired discharge rates can add up to a significant difference in pump and pipe-sizing requirements.

Sensitivity to Clogging

For the low discharge rates required in trickle irrigation, an emitter's flow channel must be about 0.01 to 0.10 in. These small passageways make all emitters susceptible to clogging and require careful filtration of all the irrigation water. Filtering to remove particles 10 or more times smaller than the emitter passageway is a typical recommendation. Some flushing-type emitters require less filtration. Long-path emitters, which have the largest passageways for a given flow rate, may still require filtering of even the smaller particles to prevent clogging.

Two characteristics that are a guide to clogging sensitivity are flow-passage size and water velocity in the passageway of the emitter. Emitter sensitivity to clogging may be classified by minimum passageway dimension as:

1. Very sensitive, for a minimum passageway dimension of less than 0.023 in.
2. Sensitive, for a minimum passageway dimension of 0.028 to 0.060 in.
3. Relatively insensitive, for a minimum passageway dimension greater than 0.060 in.

Velocities of about 14 to 20 ft/s through the emitter passageway also reduce clogging.

Emitter discharges usually are rated at a temperature of 68 °F and a pressure of 15 to 30 psi. Line-source tubing is usually rated at less than 15 psi. An orifice emitter has a flow cross section of about 0.008 to 0.024 in. and a flow capacity of 0.5 to 2.5 gph, and tends to clog easily. A long-path emitter has a flow cross section of about 0.02 to 0.055 in. and a flow capacity of 0.05 to 2.0 gph. The long-path emitters do not clog as much if velocities are high.

Some emitters have a flushing feature to reduce clogging sensitivity. Capabilities range from allowing flushing at startup and shutdown to allowing flushing continually. If the flushing control mechanism depends on gravity, it must be kept upright in the field. The continually flushing emitters have a series of orifices in a resilient material to dissipate the pressure. When the emitter clogs, line pressure builds up behind the particle and forces the orifice to expand and let the particle pass through.

Recent experience with line-source tubing has shown that clogging can be significantly reduced by regularly flushing the lateral, using either automatic flushing valves or valves connected to a separate pressure source so that all lateral ends can

be flushed by turning one valve. Even where good-quality water is used, flushing provides an added safety factor for continual operation of a system. This practice should be considered for all emitter laterals, especially if nonflushing emitters are selected.

Clearly an easy way to ascertain an emitter's sensitivity to clogging is to consider the manufacturer's recommendations for filtration. The greater the sensitivity, the finer the filtration should be. Of course local user experience based on the sensitivity to clogging of the various emitters in use locally is also a good gage of filtration requirements.

Manufacturing Variation

It is impossible to manufacture any two emitters exactly alike. The small differences between what appear to be identical emitters cause significant discharge variations.

The variations in passage size, shape, and surface finish that do occur are small in absolute magnitude but represent a relatively large percent variation. Also, some emitters use an elastomeric material to achieve a pressure-compensating or flushing ability, and such materials are inherently difficult to prepare with consistent dimensions and characteristics. The amount of difference to be expected varies with the emitter's design, materials used in its construction, and care with which it is manufactured.

The emitter coefficient of manufacturing variation (v) is used as a measure of the anticipated variations in discharge in a sample of new emitters. The value of v should be available from the manufacturer, or it can be estimated from the measured discharges of a sample set of at least 50 emitters operated at a reference pressure head. The value of v can be computed by equation 7–18.

$$v = \frac{S}{\bar{q}} \qquad \textbf{(7–18)}$$

$$= \frac{\sqrt{q_1^2 + q_2^2 \ldots + q_n^2 - n(\bar{q})^2}/\sqrt{n-1}}{\bar{q}}$$

Where

v	=	emitter coefficient of manufacturing variation.
$q_1, q_2 \ldots q_n$	=	individual emitter discharge-rate values, gallons per hour.
n	=	number of emitters in sample.
$\bar{q}$	=	average discharge rate of the emitters sampled, gallons per hour.
S	=	unbiased standard deviation of the discharge rates of the sample.

The v is a very useful characteristic with rather consistent physical significance, because the discharge rates for emitters at a given pressure are essentially normally distributed. The physical significance of v is derived from the classic bell-shaped normal distribution curves, in which:

1. Essentially all the observed discharge rates fall within $(1 \pm 3v)\bar{q}$.
2. About 95 percent of the discharge rates fall within $(1 \pm 2v)\bar{q}$.
3. The average of the low 25 percent of the discharge rates is about equal to $(1 - 1.27v)\bar{q}$.
4. About 68 percent of the discharge rates fall within $(1 \pm v)\bar{q}$.

Thus, for an emitter having $v = 0.06$ (which is average) and $\bar{q} = 1.0$ gph, 95 percent of the discharges can be expected to fall within the range of 0.88 to 1.12 gph, and the average discharge of the low 25 percent will be about 0.92 gph.

As a general guide, manufacturing variation can be classified as:

Drip and spray emitters	
$v \leq 0.05$	excellent
$0.05 < v \leq 0.07$	average
$0.07 < v \leq 0.11$	marginal
$0.11 < v \leq 0.15$	poor
$0.15 < v$	unacceptable

Line-source tubing	
$v \leq 0.10$	good
$0.10 < v \leq 0.20$	average
$0.20 < v$	poor to unacceptable

A lower standard is used for line-source tubing because it is difficult to keep both the variation and the price low; the outlets are normally closely spaced; and row crop production is relatively insensitive to moderate variations in closely spaced water application.

System Coefficient of Manufacturing Variation

The system coefficient of manufacturing variation (v_s) is a useful concept because more than one emitter or emission point may be used per plant. In such

an instance, the variations in flow rate for each emitter around the plant partly compensate for one another. One emitter might have a high flow rate and another would probably have a low flow rate; on the average, the variation in the total volume of water delivered to each plant is less than might be expected from considering v alone. The v_s can be computed by equation 7–19.

$$v_s = \frac{v}{\sqrt{e'}} \qquad (7\text{–}19)$$

Where

v = emitter coefficient of manufacturing variation.

e′ = minimum number of emitters per plant, or 1 if one emitter is shared by more than one plant.

Line-source systems may have only one outlet per plant; however, because of the close spacing of outlets, each plant may receive its water from two outlets. If multioutlet emitters with small-diameter distribution tubing are used (fig. 7–10), the proper value of e′ depends on the design of the individual emitter. If one common loss element serves several outlets, e′ is equal to 1. If there is a separate pressure-loss passageway for each outlet, then the emitter is really multiple emitters in a single housing, and e′ is the number of outlets. It should be emphasized that v is a property of the emitter alone, and v_s is a property of the trickle irrigation system as a whole.

Sprayers must apply a relatively uniform depth of water to the directly wetted soil surface. Some variation between emitters in the areal depth applied is acceptable, but differences in distribution of soil moisture are likely to be unacceptably great when the depth of application varies by more than 2:1 between points 3 ft or farther apart.

Relation of Pressure to Discharge

The relation between changes in pressure head and discharge is a most important characteristic of emitters. Figure 7–22 shows this relationship for various types of emitters. The emitter discharge exponent (x) measures the flatness of the discharge-pressure curve, and the desirability of an emitter that has a discharge-pressure curve with a low x is clear. Compensating emitters have a low x; however, since they all have some physical part that responds to pressure, their long-range performance requires careful consideration. The compensating emitters usually have a high coefficient of manufacturing variation (v), and their performance may be affected by temperature, material fatigue, or both.

On undulating terrain the design of a highly uniform system is usually constrained by the pressure sensitivity of the average emitter. Compensating emitters provide an immediate solution. Emitters of various sizes may be placed along the lateral to meet pressure variations resulting from changes in elevation. The practicality of using emitters of more than one size in the field should to be assessed.

The lateral length, even on smooth fields, must be kept reasonably short to avoid excessive differences in pressure. Factors affecting the maximum length of run are the flow rate per plant, the emission uniformity, the emitter selected, the lateral pattern, and the terrain. In some installations, field dimensions and cultural practices affect the maximum length of run.

In laminar-flow emitters, which include the long-path, low-discharge devices, the relation between the discharge and the operating pressure is linear, i.e., doubling the pressure doubles the discharge. Therefore, the variations in operating pressure head within the system are often kept to within ±5 percent of the desired average.

In turbulent-flow emitters, the change in discharge varies with the square root of the pressure

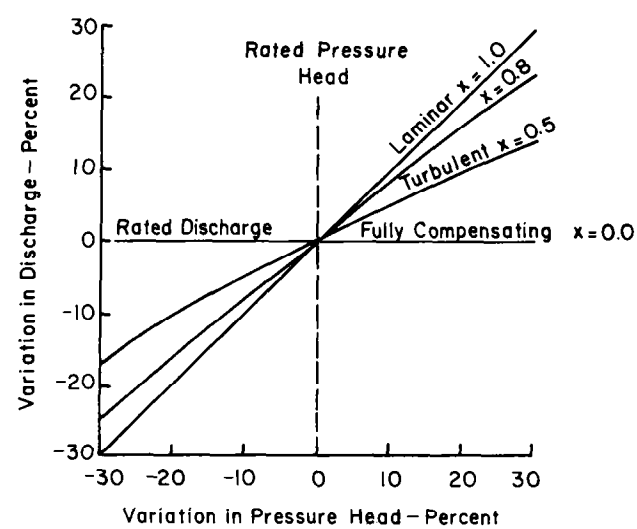


Figure 7–22.—Discharge variations resulting from pressure changes for emitters with various discharge exponents (x).

head, i.e., x = 0.5, and the pressure must be increased four times to double the flow. Therefore, the pressure head in systems with turbulent-flow emitters is often allowed to vary by ±10 percent of the desired average.

Flow-compensating emitters regulate flow to various degrees, and x may be less than 0.5. If flow regulation is absolute, x = 0.0. Absolute flow regulation might be undesirable, however, if it ever became necessary to compensate for underdesign or for decreased emitter discharges resulting from slow clogging or emitter deterioration, because increases in pressure would not increase flow. When x ranges between 0.3 and 0.4, flow is substantially regulated (i.e., a 50-percent head differential would cause only a 13- to 18-percent variation in discharge, and some compensating ability would also be maintained). Compensating emitters are valuable chiefly for use on hilly sites where designing for uniform pressure along the laterals and manifolds is impractical.

Relation of Temperature to Discharge

An emitter may be sensitive to water temperature for any of three reasons. Some emitters are designed so that their flow rate depends on the viscosity of the water, which changes with temperature. Most emitters are somewhat sensitive to water temperature because of dimensional changes in the flow passage. Emitters with parts made of resilient material (e.g., pressure-compensating emitters) may be subject to variation in flow from a change in material characteristics caused by changing temperature.

There is a temperature difference between the air and water in the pipe, especially if the lateral pipe lies in the sun. As the water moves through the system and changes temperature (usually warming), the uniformity of the discharge may also change. A small decrease in viscosity resulting from water warming as it flows toward the ends of laterals may partially compensate for the usual decrease in pressure.

Connection Losses

The three main types of lateral connections are in-line, on-line, and on-line-riser. Figure 7–17 shows that the in-line connection has the simplest configuration. On-line-risers are used in subsurface applications. But the subsurface method is cost effective only when the emitter spacing is wide, or where it provides agronomic advantages.

Stress cracking caused by emitter barbs' stretching the lateral wall can be a problem. Excess stress causes premature aging at the joint, resulting in cracks and leakage, and in extreme cases the emitters may blow out. This potential hazard can be prevented by connecting on-line emitters to the lateral with barbs in properly sized, smooth-edged, punched-out holes. In-line emitters should be provided with compression barbs or compression ring fittings.

The emitter-connection friction loss as an equivalent length of lateral (f_e) is a useful term in estimating loss from friction in laterals. The f_e depends on the size and type of barb and on the inside diameter (ID) of the lateral. Figure 7–23 gives estimated f_e values for in-line emitters and for on-line barbs of three different sizes as a function of the ID of the lateral.

Performance

Test data for a number of emitters are presented in table 7–5. All tests were made with clean water at a standard temperature of 68 °F on new emission devices obtained from retail outlets. A summary of the test results follows:

1. The emitter discharge exponents (x) for the devices tested ranged from 0.11 to 1.0. Emitters having x values less than 0.5 may be termed "pressure compensating." Pressure compensation is not a

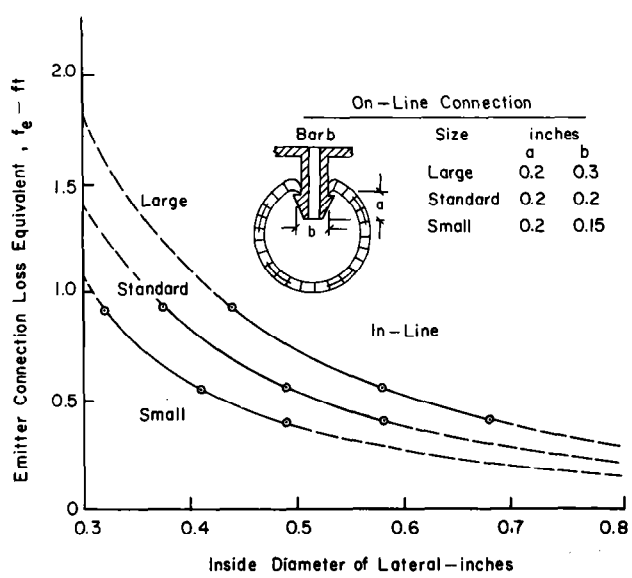


Figure 7–23.—Emitter-connection loss (f_e) values for various sizes of barbs and inside diameters of laterals

yes-or-no feature of emission devices; available devices had various degrees of compensation.

2. Measured emitter coefficients of manufacturing variability (v) ranged from 0.02 to 0.40. Most devices seemed to be manufactured with a consistency of $v \cong 0.06$.

3. The temperature-discharge ratio (TDR) revealed a wide range of discharge sensitivity to water temperature. At an elevated temperature, some devices discharged as much as 21 percent less than normal, but one discharged nearly four times normal flow. Several devices, however, were relatively insensitive to water temperature.

Generalizing from these data requires care. Emitters of the same design may have quite different performance characteristics, depending on the materials used in their construction and the care and precision with which they were manufactured. Table 7–5 provides a useful guide for the probable characteristics and important features of the various types of emitters.

Discharge Exponent

The emitter discharge exponent (x) characterizes the flow regime and discharge-versus-pressure relationship of the emitter. The emitter discharge (q), gallons per hour, for most emitters or sprayers can be computed by equation 7–20.

Table 7–5.—Test characteristics of emission devices[1]

Emission device[2]	x[3]	v[4]	TDR[5] 113 °F	TDR[5] 149 °F	MFPD[6]	Flushing ability
					Inches	
Orifice						
Vortex/orifice	0.42	0.07	0.92	0.88	0.024	None
Multiple flexible	0.7	0.05	1.04	1.07	—	Continuous
orifices	0.7	0.07	1.04	1.07	—	Continuous
Ball & slotted	0.50	0.27	1.15	1.21	(0.012)	Automatic
seat	0.49	(0.25)	0.83	0.79	(0.012)	Automatic
Compensating ball	0.15	0.35	0.85	0.81	0.012	Automatic
& slotted seat	0.25	0.09	0.90	0.89	(0.012)	Automatic
Capped orifice	0.56	(0.05)	(1.03)	(1.05)	0.04	None
sprayers	0.53	(0.05)	(1.03)	(1.05)	0.06	None
Long path						
Small tube	0.70	0.05	1.08	1.13	0.039	None
	0.80	0.05	1.16	1.22	0.039	None
Spiral path	0.75	0.06	1.19	1.18	0.031	Manual
	0.65	0.02	(1.10)	(1.15)	0.028	None
Compensating	0.40	0.05	1.19	1.33	(0.030)	None
	0.20	0.06	1.11	1.24	(0.030)	Automatic
Tortuous	0.50	(0.08)	1.40	1.70	0.031	None
	0.65	0.02	1.08	1.14	(0.039)	None
Short path						
Groove & flap	0.33	0.02	1.00	1.00	0.012	Automatic
Slot & disc	0.11	0.10	1.06	1.08	0.012	Automatic
Line source						
Porous pipe	1.0	0.40	2.70	3.80	—	None
Twin chamber	0.61	0.17	(1.05)	(1.10)	(0.016)	None
	0.47	(0.10)	(1.04)	(1.08)	(0.016)	None

[1]Test data at a standard operating temperature of 68 °F. Numbers in parentheses are estimates.
[2]Double entries indicate different devices of the same general type.
[3]Emitter discharge exponent (eq. 7–20).
[4]Emitter coefficient of manufacturing variation (eq. 7–18).
[5]Temperature-discharge ratio, the ratio of the emitter discharge at a temperature higher than 68 °F to that at 68 °F.
[6]Minimum flow-path dimension—not meaningful with continuous flushing.

$$q = k_d h^x \qquad (7\text{–}20)$$

Where

k_d = constant of proportionality (discharge coefficient) that characterizes each emitter.
h = working pressure head at the emitter or sprayer, pounds per square inch.

The x for the discharges at two operating pressure heads can be determined by equation 7–21.

$$x = \frac{\log (q_1/q_2)}{\log (h_1/h_2)} \qquad (7\text{–}21)$$

Where

q_1, q_2 = emitter discharges, gallons per hour.
h_1, h_2 = pressure heads corresponding to q_1, q_2, respectively, pounds per square inch.

The x for the discharges at two operating pressure heads may also be obtained graphically by measuring the slope of the line connecting the two discharge values and respective pressure-head values plotted on log-log graph paper.

Sample calculations.—Determine graphically the discharge exponent and discharge coefficient from discharge-versus-pressure head data for a vortex emitter, and find the head required to produce any given discharge.

Given: Emitter discharges (q), at pressure heads (h): 1.00 gph at 10.0 psi, 1.34 gph at 20.0 psi.

Find: Discharge exponent (x) and pressure head (h) at which q = 1.20 gph (fig. 7–24).

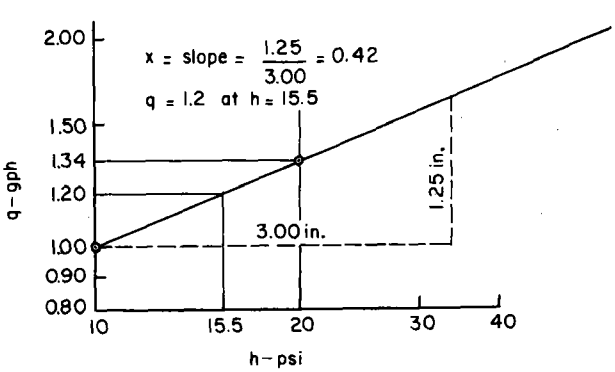


Figure 7–24.—Graphical method for determining the discharge exponent (x) in a sample calculation.

Types of Emitters

Long-Path Emitters

Most of the head loss in a smooth long-path emitter (fig. 7–25) occurs in the long-flow-path section. The flow in this section is laminar. Laminar-flow emitters are quite sensitive to pressure differences in the trickle system. The length of the path needed for a required loss of head and a known discharge for a laminar-flow range in a long-path emitter with a circular cross section can be computed by equation 7–22.

$$l_c = \frac{hgd^4\pi}{98.6q\nu} \qquad (7\text{–}22)$$

Where

l_c = length of the flow path in the emitter, feet.
h = working pressure head of the emitter, feet.
g = acceleration of gravity (32.2 ft/s²).
d = flow cross-section diameter, inches.
q = emitter discharge, gallons per hour.
ν = kinematic viscosity of water, square feet per second.

The spiral effects of flow at entrance and other irregularities in the long-path emitters create considerable turbulence. If turbulence exists, emitter head-loss characteristics computed by equation 7–22 would not be correct and the emitter should be evaluated as a tortuous-path emitter.

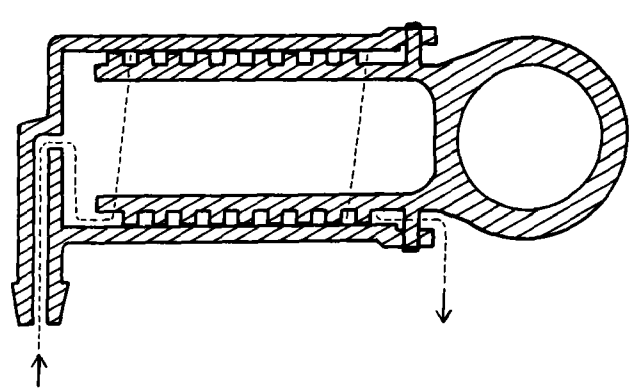


Figure 7–25.—Cross section of a long-path emitter that can be opened for easy cleaning.

Tortuous- and Short-Path Emitters

Tortuous-path emitters have relatively long flow paths. Pressure head loss is caused by a combination of wall friction, sharp bends, contractions, and expansions. Some tortuous-path emitters look similar to ordinary long-path emitters; however, their flow channel is typically shorter and the cross section is larger for the same discharge (q). Since the flow regime is almost fully turbulent, the q varies more nearly with the square root of the working pressure head (h) than with h itself.

Short-path emitters generally behave like orifice emitters because the entrance characteristics (losses) dominate the flow in the short tube section. However, many short-path emitters are pressure compensating; this is explained under Compensating Emitters.

Orifice Emitters

The flow in orifice emitters is fully turbulent. Many drip and spray emitters and single-chamber line-source tubing are classified as orifice emitters. In a nozzle or orifice emitter, water flows through a small-diameter opening or series of openings where most of the pressure head loss takes place. The discharge of the orifice emitter (q), gallons per hour, can be computed by equation 7–23.

$$q = 187ac_q\sqrt{2gh} \qquad \textbf{(7–23)}$$

Where

- a = flow cross section, square inches.
- c_q = coefficient that depends on the characteristics of the nozzle; c_q ranges from 0.6 to 1.0.
- g = acceleration of gravity (32.2 ft/s²).
- h = working pressure head of emitter, feet.

Twin-Chamber Tubing

Most of the pressure head loss in twin-chamber tubing (fig. 7–15) occurs in the inner orifice. The q of twin-chamber tubing can be computed by equation 7–24.

$$q = 187ac_q\sqrt{2g(h - h^1)} \qquad \textbf{(7–24)}$$

Where

- h = working pressure head of the inner main chamber, feet.
- h^1 = working pressure head of the secondary chamber, feet.

Normally, the main and secondary chambers of twin-chamber tubing are the same diameter, and there are three to six orifices in the secondary chamber for each orifice in the main chamber. The h^1 of the secondary chamber can be computed by equation 7–25.

$$h^1 = \frac{h}{1 + m^2} \qquad \textbf{(7–25)}$$

Where

- m = number of orifices in the secondary chamber per orifice in the main chamber.

Vortex Emitters and Sprayers

The vortex emitter or sprayer has an orifice containing a circular cell that causes vortical flow. The entrance of the water tangent to the inner wall causes the water to rotate rapidly, resulting in a vortex in the center of the cell. Consequently, both the resistance of the flow and the head loss are greater in the vortex emitter than in a simple orifice of the same diameter. Vortex emitters can be constructed to give an approximate discharge (q), gallons per hour, that can be computed by equation 7–26.

$$q = 187ac_q\sqrt{2g}\, h^{0.4} \qquad \textbf{(7–26)}$$

Where

- a = flow cross section, square inches.
- c_q = coefficient for characteristics of the orifice; about 0.4.
- g = acceleration of gravity (32.2 ft/s²).
- h = working pressure head of emitter, feet.

The c_q value of about 0.4 gives a discharge of about one-third of the flow of a simple orifice of the same diameter. Therefore, for the same discharge and pressure head, the entrance diameter of a vortex emitter can be about $\sqrt{3}$, or 1.73, times larger than that of a simple-orifice emitter.

Compensating Emitters

Compensating emitters (fig. 7–16) are constructed to yield a nearly constant discharge over a wide

range of pressures. Both long-path or short-path and orifice-type compensating emitters are available. Orifice and tube diameters at each given pressure should be computed as shown, but the diameters change with pressure. A peculiar problem of compensating emitters is that the resilient material may distort over a period of time and gradually squeeze off the flow, even though pressure remains constant. The emitter discharge (q), gallons per hour, can be computed by equation 7–27 for orifice and short-tube compensating emitters.

$$q = 187ac_q\sqrt{2g}\,h^x \qquad \textbf{(7–27)}$$

Where

- a = flow cross section, square inches.
- c_q = coefficient for characteristics of the emitter.
- g = acceleration of gravity (32.2 ft/s²).
- h = working pressure head of the emitter, feet.
- x = discharge exponent; varies from 0.5 to 0.0, depending on the characteristics of the flow section and the resilient material used.

Flushing Emitters

There are two types of self-flushing emitters, on-off flushing and continuous flushing. On-off-flushing emitters (fig. 7–16) flush for only a few moments each time the system starts operating, then shut off. This behavior is typical of the compensating type.

Continuous-flushing emitters are constructed so that they can eject relatively large particles during operation by using a series of relatively large-diameter flexible orifices to dissipate pressure. As shown in figure 7–26, particles larger than the orifice diameter are ejected by localized pressure buildup as they reach each flexible orifice.

In continuous-flushing emitters, the orifice is sensitive to pressure changes and the orifice material is sensitive to temperature. For emitters with flexible orifices that tend to expand under pressure, an approximate discharge (q), gallons per hour, can be computed by equation 7–28.

$$q = 187ac_q\sqrt{2g}\,(h/m')^{0.7} \qquad \textbf{(7–28)}$$

Where

- a = flow cross section area, square inches.
- c_q = coefficient that depends on the characteristics of the orifice; ranges from 0.6 to 1.0.
- g = acceleration of gravity (32.2 ft/s²).
- h = working pressure head of the emitter, feet.
- m′ = the number of orifices in series in the emitter.

For continuous-flushing emitters that have a series of rigid orifices, q can be computed by equation 7–29.

$$q = 187ac_q\sqrt{2gh/m'} \qquad \textbf{(7–29)}$$

Emitter Operating Characteristics

Discharge

The recommended operating range and the relationship between average emitter discharge (q_a) and pressure should be available from the emitter's manufacturer. Often emitter sizes are given in terms of a rated average discharge at some standard pressure head along with a discharge exponent.

The first step in determining the volume of the emitter discharge is to select an emitter that has a rated discharge (or the discharge at the midpoint of

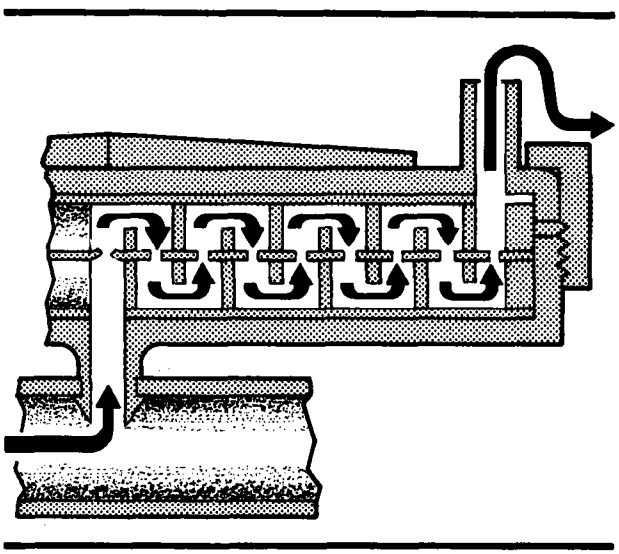


Figure 7–26.—Cross section of a continuous-flushing emitter.

the recommended range) that appears to be appropriate for the system. The q_a should be large enough to supply the crop needs during the period of peak use when operating about 20 hr per day, but small enough so that it does not cause runoff.

Let q_a be equal to the rated discharge of the selected trial emitter, gallons per hour. The time of application (T_a), hours per day, for the gross volume of water required per plant during the peak use period can be computed by equation 7–30.

$$T_a = \frac{F_{(gp/d)}}{eq_a} \qquad (7\text{–}30)$$

Where

$F_{(gp/d)}$ = gross volume of water required per plant per day during the peak use period, gallons per day.

e = number of emitters per plant.

The maximum number of hours of operation per day should not exceed 90 percent of the available time (i.e., 21.6 hr/day). The nonoperation time is a margin of safety for system failure or other unexpected down time. It may be necessary to analyze the system by number of stations (N) to apply water within 21.6 hr/day (fig. 7–27). To determine N, select a reasonable T_a, between 12 and 21.6 hr/day, and compute a new q_a.

When the preliminary value of T_a computed by equation 7–30 is greater than 21.6 hr/day (even for a single-station system), the emitter discharge would need to be increased above the rated discharge. If the increased discharge exceeds the recommended range or requires too much pressure, either larger emitters or more emitters per plant are required. Examples of decision strategies for other preliminary T_a values are:

1. If $T_a \cong 21.6$ hr/day, use a one-station system (N = 1), select $T_a \leq 21.6$ hr/day, and adjust q_a accordingly.
2. If $T_a \cong 10.8$ hr/day, use N = 2, select $T_a \leq 10.8$, and adjust q_a accordingly.
3. If $12 < T_a < 18$, it may be desirable to use another emitter or a different number of emitters per plant to enable operating closer to 90 percent of the time and thereby reduce investment costs.

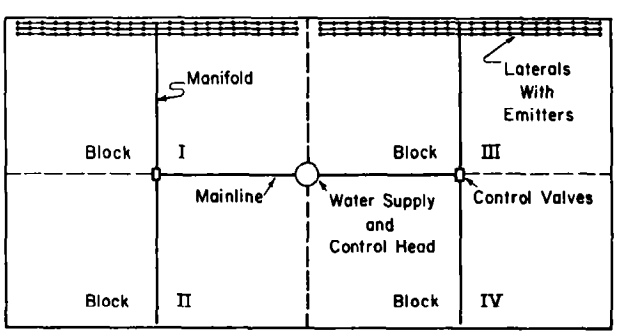


Figure 7–27.—Typical two-station split-flow layout for trickle irrigation system with Blocks I and III, or II and IV, operating simultaneously.

Average Pressure

Normally, published data for the emitter are a series of pressure heads vs. discharges. For determining the average emitter pressure head (h_a), feet, for a desired average discharge (q_a), gallons per hour, the basic emitter discharge equation needs to be modified. The h_a for a given discharge can be computed by equation 7–31.

$$h_a = \left(\frac{q_a}{k_d}\right)^{1/x} \qquad (7\text{–}31)$$

Where

k_d = constant of proportionality (discharge coefficient) that characterizes each emitter.

x = emitter discharge exponent.

Emission Uniformity

Emission uniformity (EU) from all the emission points within a trickle irrigation system is important because it is one of the major components of irrigation efficiency. From field test data EU, percent, can be computed by equation 7–32.

$$EU = 100\, q_n'/q_a' \qquad (7\text{–}32)$$

Where

q_n' = average discharge of the lowest 25 percent of the field-data discharge readings, gallons per hour.

q_a' = average of all the field-data emitter discharges, gallons per hour.

In the design phase, the variation expected in emission rates must be estimated by some analyti-

cal procedure. Unfortunately, it is not practical to consider in a formula for EU all the influencing factors, such as full or partial clogging, changes in water temperature, and aging of emitters. It is not possible to look at a design and compute or even satisfactorily estimate the unpredictable variations in emission rates these factors may cause. Other items, however, can be known. The manufacturer should provide information about the relation of pressure to rate of emission and also about manufacturing variation for the emitter. Topographic data from the intended site and a hydraulic analysis of the proposed pipe network can give the needed information about expected variation in pressure.

The basic concept and formulas for EU were initially published in studies by Keller and Karmeli.[3] The basis of their formula is the ratio of the lowest emission rate to the average emission rate. This process treats below-average emission rates as more important than those above average and treats the lowest emission rates as more important than those somewhat below average. This scheme seems reasonable for evaluating trickle irrigation, which applies reduced amounts of water to the plant and irrigates only a part of the plant's root zone. In trickle irrigation, underwatering is a greater hazard than overwatering.

For a proposed design, an estimate of EU can be computed by equation 7–33a or 7–33b:

$$EU = 100(1.0 - 1.27\frac{v}{\sqrt{e'}})\frac{q_n}{q_a} \qquad \textbf{(7–33a)}$$

$$EU = 100(1.0 - 1.27v_s)\frac{q_n}{q_a} \qquad \textbf{(7–33b)}$$

Where

- v = coefficient of manufacturing variation of the emitter, obtained from the manufacturer or by equation 7–18.
- v_s = system coefficient of manufacturing variation (eq. 7–19).
- e' = minimum number of emitters per plant.
- q_n = minimum emission rate computed from the minimum pressure in the system, based on the nominal flow rate-vs.-pressure curve, gallons per hour.
- q_a = average or design emission rate, gallons per hour.

The ratio of q_n to q_a expresses the relationship of minimum to average emission rate that results from pressure variation within the system. The 100 is needed to convert the ratio to a percentage. The factor in the middle adjusts for the additional nonuniformity caused by anticipated manufacturing variation between individual emitters.

Allowable Pressure-Head Variation

The allowable pressure-head variation ($\triangle H_s$) is the pressure-head variation between emitters in a subunit that will give the design emission uniformity (EU). The subunit may be the manifold and attached laterals, a group of laterals, or a single lateral, depending on where the pressure is regulated. Figure 7–28 is a schematic of the pressure-head distribution in a simple subunit. Figure 7–29 shows an example of the combined effect of pressure-head and manufacturing variations on individual emitter discharges. The particular example depicted is for a subunit on a level field with constant-diameter manifolds and laterals in which $\triangle H_s$ = 10 ft when the pressure head (h_a) that gives the average or design emitter discharge rate (q_a) is 40 ft. This gives a subunit head-loss ratio of 0.25. The emitter characteristics are q_a = 0.91 gph, emission discharge coefficient (x) = 0.72, and manufacturer's coefficient of variation (v) = 0.033.

In figure 7–29 the region of emitter discharges is bounded on the sides by the minimum and maximum pressures in the subunit. The bottom and top of the region are bounded by the minimum and maximum discharge expected from a test sample of emitters at each possible operating pressure. The $\triangle H_s$ in the subunit on a level field is caused by the friction loss. The h_a, which gives the q_a, is not midway between the extremes of pressure, because loss of pressure is greatest in the first part of constant-diameter manifolds and laterals.

The uniformity of amounts of water emitted throughout a subunit is determined by the EU, because all the emitters are operated for the same application time (T_a). Selecting the ideal design EU requires economic trade-offs. Four factors must be considered: (1) cost required to install systems with increased EU; (2) water and water-related costs; (3) sensitivity of crop yield and quality to non-

[3]Keller, J., and Karmeli, D. 1975. Trickle irrigation design. Rainbird Sprinkler Mfg. Corp., Glendora, Calif., 133 pp.

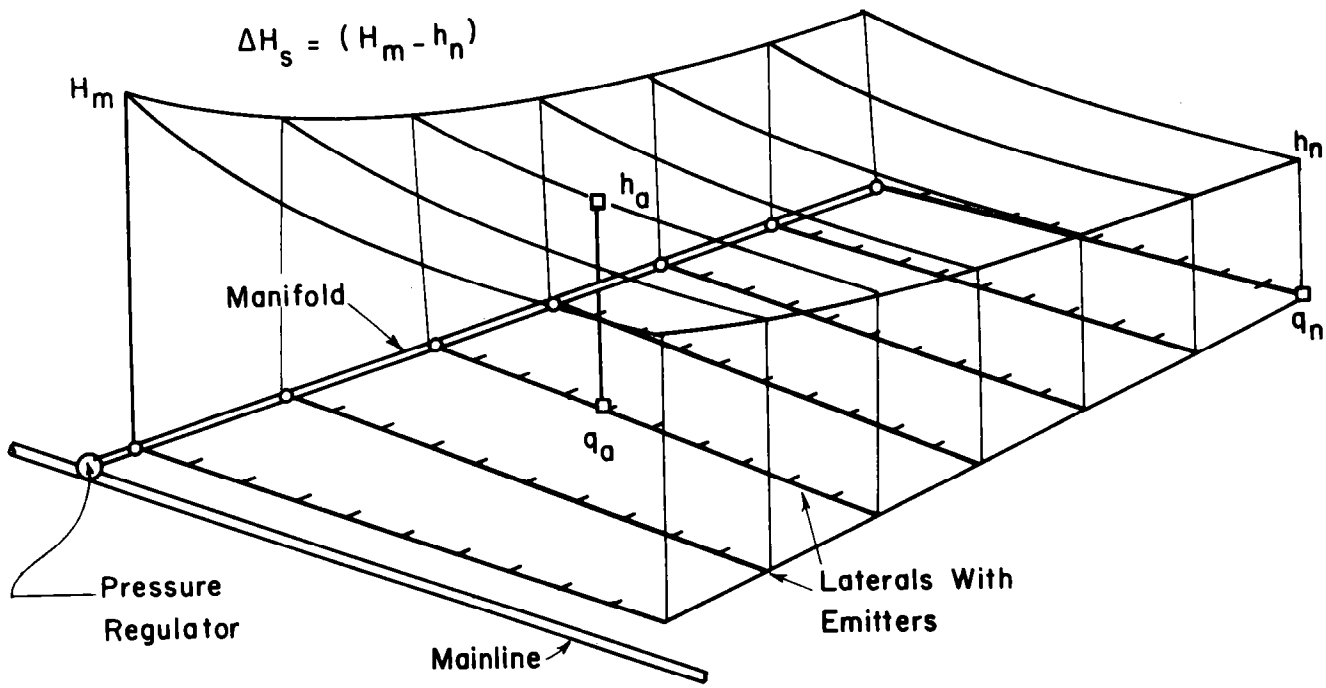


Figure 7-28.—Distribution of a pressure head in a subunit. ΔH_s = allowable pressure-head variation; H_m = manifold inlet pressure head; h_n = pressure head that gives the q_n required to satisfy the design emission uniformity; h_a = pressure head that gives the q_a; q_a = average or design emitter discharge rate; q_n = minimum emitter discharge.

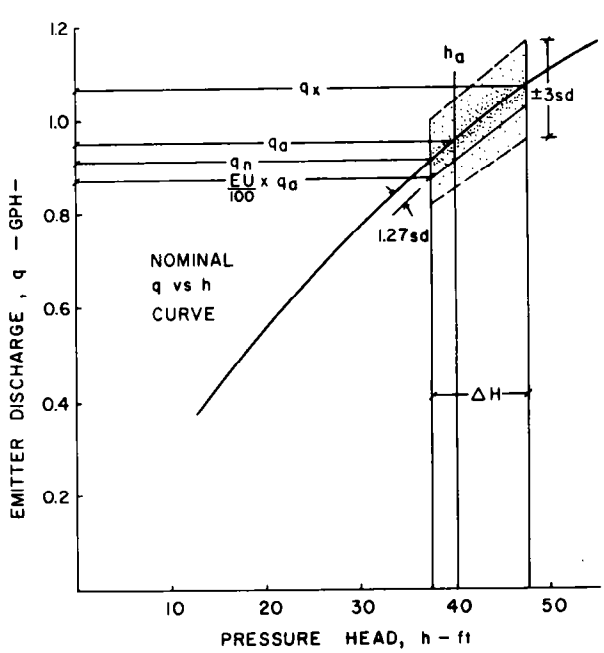


Figure 7-29.—Combined effect of pressure-head and manufacturing variations on discharges of individual emitters. h_a = pressure head that gives the average or design emitter discharge rate; sd = standard deviation; q_x = largest flow rate; q_a = average or design emitter discharge rate; q_n = minimum emitter discharge rate; EU = emission uniformity.

uniform irrigation; and (4) market values of the crop. An economic analysis of these factors can determine the optimal EU in any specific situation, but usually data are insufficient for such an analysis. For design purposes, the recommended ranges of EU values to use in conjunction with equation 7-33 are as follows:

1. For emitters in widely spaced permanent crops with:
   a. uniform topography, 90-94
   b. steep or undulating topography, 88-92
2. For emitters in closely spaced (<6 ft) permanent and semipermanent crops with:
   a. uniform topography, 86-90
   b. steep or undulating topography, 84-90
3. For line-source tubing on annual row crops with:
   a. uniform topography, 80-90
   b. steep or undulating topography, 70-85

The minimum emitter discharge that will satisfy the desired EU value (q_n) can be determined by solving equation 7-33 for q_n, i.e., using the q_a determined from equation 7-30 and the system coefficient of manufacturing variation (v_s) for the selected emitter and layout.

The pressure head that gives q_n for the selected emitter (h_n), feet, can be determined from equation 7–20. From h_a and h_n the $\triangle H_s$, feet, can be computed for design purposes by equation 7–34.

$$\triangle H_s = 2.5(h_a - h_n) \qquad \textbf{(7–34)}$$

Where

h_a = pressure head that will give the q_a required to satisfy equation 7–30, feet.
h_n = pressure head that will give the q_n required to satisfy equation 7–33 with the design EU, feet.

Maintaining the design EU requires keeping the pressure head between h_n and ($h_n + \triangle H_s$) while differentials in both pipe friction and elevation are included. If the calculated $\triangle H_s$ is too small for economic design purposes, the options are to (1) select another emitter that has a lower coefficient of manufacturing variation (v), discharge exponent (x), or both; (2) increase the number of emitters per plant (e); (3) use a different emitter or rearrange the system to get a higher h_a; or (4) relax the design EU requirement.

Total System Capacity

Knowledge of the total system capacity (Q_s), gallons per minute, is necessary to design an economical and efficient pumping plant and pipeline network. The system capacity for any emitter layout can be computed by equations 7–35a and 7–35b.

$$Q_s = 726 \frac{A}{N} \frac{eq_a}{S_p S_r} \qquad \textbf{(7–35a)}$$

Where

A = field area, acres.
e = number of emitters per plant.
N = number of operating stations.
q_a = average or design emission rate, gallons per hour.
S_p = plant spacing in the row, feet.
S_r = distance between plant rows, feet.

For uniformly spaced laterals that supply uniformly spaced emitters:

$$Q_s = 726 \frac{A}{N} \frac{q_a}{S_e S_l} \qquad \textbf{(7–35b)}$$

Where

S_e = spacing between emitters on a lateral, feet.
S_l = spacing between laterals, feet.

For computing total system capacity where line-source tubing is used and the discharge rate is per 100 ft of tubing, equation 7–36 can be used.

$$Q_s = 726 \frac{A}{N} \frac{e}{S_p} q_a \qquad \textbf{(7–36)}$$

Where

q_a = (q_a per 100 ft of tubing)/100.

Pump Operating Time per Season

The pump operating time per season (Q_t), hours, can be estimated by equation 7–37 with the gross seasonal volume (V_i), acre-feet, computed by equation 7–14 and the total system capacity (Q_s), gallons per minute.

$$Q_t = 5{,}430 \frac{V_i}{Q_s} \qquad \textbf{(7–37)}$$

Some systems require extra capacity because of anticipated slow changes in average emitter discharge (q_a) with time. Decreases in q_a can result from slow clogging from sedimentation in long-path emitters or compression of resilient parts in compensating emitters. Increases in q_a can result from mechanical or chemical fatigue of the flexible orifices in continuous- and periodic-flushing emitters or increases in minor leakage from fatigue in emitters and tubing.

Both decreases and increases in q_a necessitate periodic cleaning or replacement of emitters. A decrease in discharge rate can be compensated for by operating the system either at a higher pressure or for a longer time during each irrigation application. The need for frequent cleaning or replacement of emitters because of decreasing discharge rates can be prevented by designing the system with 10 to 20 percent extra capacity. By following the recommended design procedure, based on a maxi-

mum operation time of 21.6 hr/day during the peak use period, 10 percent extra capacity is already available. A possible alternative is to provide enough reserve operating pressure so that the pressure can be increased as required to hold q_a constant until the emitter discharge characteristics have degenerated by 10 to 20 percent.

Providing extra system capacity necessitates increasing the pump and pipe size, whereas providing reserve operating pressure requires only a slightly larger pump. Consequently, the cost of providing reserve pressure is less then the cost of providing extra capacity. Nonetheless, systems that have extra capacity can better make up for unavoidable interruptions before the emitter discharge has decreased. Furthermore, they can also handle situations when minor leakage increases q_a.

Net Water-Application Rate

The net water-application rate (F_n), inches per hour, is the water applied to the plants at the lowest discharge rate of the emission device. The application rate is important in irrigation scheduling because it is needed to calculate the number of hours that the system must operate to apply a specific volume of water.

The F_n is a function of the minimum expected rate of emitter discharge (q_n), gallons per hour, and thus cannot be computed until the hydraulic network has been designed. The q_n is a function of the minimum expected pressure head (h_n), feet, in the system and can be computed by equation 7–38.

$$q_n = q_a \left(\frac{h_n}{h_a}\right)^x \qquad \textbf{(7–38)}$$

Where

q_a = average emitter discharge, gallons per hour.
h_a = average pressure head of emitter, feet.
x = emitter discharge exponent.

If the friction head loss in a trickle irrigation system is greater than the head gain from elevation drops, h_n can be computed by equation 7–39.

$$h_n = (H_m - \triangle H_m - \triangle h) \qquad \textbf{(7–39)}$$

Where

H_m = manifold inlet pressure head, feet.
$\triangle H_m$ = difference in pressure head along the manifold, feet.
$\triangle h$ = difference in pressure head along the lateral, feet.

Steep downhill manifolds and laterals in which the friction loss is less than the head gain from elevation drops will have lower pressures at the inlet than further down the line. In such cases, h_n must be determined by inspection of the graphical solutions.

With an estimated q_n and the final design emission uniformity (EU), the F_n can be computed by equation 7–40.

$$F_n = 1.604 \frac{EU}{100} \frac{eq_a}{S_p S_r} \qquad \textbf{(7–40)}$$

Where

e = number of emitters per plant.
S_p = distance between plants in the row, feet.
S_r = distance between plant rows, feet.

The maximum daily net water application that the system can apply in an emergency is 24 hr × F_n.

Computing Injection of Fertilizer and Chemicals

The rate at which any concentration of chemical is to be injected into the irrigation water should be calculated carefully.

The rate of injecting fertilizer into the system (q_f), gallons per hour, depends on the concentration of the liquid fertilizer and the quantity of nutrients to be applied during the irrigation. The rate can be computed by equation 7–41.

$$q_f = \frac{F_r A}{H F_c H_r} \qquad \textbf{(7–41)}$$

Where

F_r = fertilizer rate (quantity of nutrients to be applied per irrigation cycle), pounds per acre.

H = time of irrigating per irrigation cycle, hours.
A = area irrigated per irrigation cycle, acres.
H_r = ratio between hours of fertilizing and hours of irrigating per irrigation cycle.
F_c = concentration of nutrients in the liquid fertilizer, pounds per gallon.

Capacity of the fertilizer tanks.—The capacity of the fertilizer tanks is an important consideration. Large, low-cost tanks are practical for use with injection pumps. A large tank is a good place to store fertilizer for periods when supply is short, and its use reduces the labor associated with frequent filling. If a large tank is being used, shutoff is a convenient way to control the amount of fertilizer injected.

For a pressure-differential injection system, a high-pressure fertilizer tank should hold enough for a complete application. Required tank capacity (C_t), gallons, can be computed by equation 7–42.

$$C_t = \frac{F_r A}{F_c} \qquad (7\text{–}42)$$

Where

F_r = fertilizer rate (quantity of nutrients to be applied per irrigation cycle), pounds per acre.
A = area irrigated per irrigation cycle, acres.
F_c = concentration of nutrients in the liquid fertilizer, pounds per gallon.

Rate of injecting chlorine or acid.—The rate of injecting chlorine or acid depends on the system's flow rate. Liquid chlorinators are usually preferred over gas chlorinators because:

1.. A gas chlorinator is used for chlorination only, whereas a positive displacement pump can inject not only liquid chlorine and fertilizers, but also micronutrients, fungicides, herbicides, acids, and other liquids as needed.

2. A gas chlorinator usually costs 4 to 10 times as much as a pump.

3. Because chlorine gas is extremely hazardous, it is expected that, for installing a gas chlorinator, the Occupational Safety and Health Administration (OSHA), will require the use of a separate building and special handling of the gas cylinders.

4. Most manufacturers of trickle irrigation hardware make filtration equipment and provide the chemical solution tanks and chemical injection systems as part of their systems for filtration, water treatment, and chemical feeding.

The rate of injecting a chemical such as chlorine or acid (q_c), gallons per hour, can be calculated by equation 7–43.

$$q_c = \frac{0.006CQ_s}{csg} \qquad (7\text{–}43)$$

Where

C = desired dosage, parts per million.
Q_s = irrigation system capacity, gallons per minute.
c = concentration of the desired component in liquid chemical concentrate, percent.
sg = specific gravity of the chemical concentrate.

Pipeline Hydraulics

This section contains data and information about the hydraulic aspects of pipe systems important in the design of trickle irrigation systems. For more general information on the subject, refer to Section 5, Hydraulics, of this National Engineering Handbook.

Friction Loss in Pipelines

Plastic is the predominant pipe material used for trickle irrigation laterals, manifolds, and main lines. The Hazen-Williams formula is the basis for many friction-loss calculations. Equation 7–44 can be used to calculate the head loss gradient (J), feet per 100 feet, by the Hazen-Williams formula.

$$J = \frac{h_f 100}{L} = 1{,}050 \frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} \qquad (7\text{–}44)$$

Where

h_f = head loss from pipe friction, feet.
L = pipe length, feet.
Q = flow rate in the pipe, gallons per minute.
C = friction coefficient for continuous sections of pipe.
D = ID of the pipe, inches.

Typically, C = 150 has been used to calculate friction losses in plastic pipe. The inner surface of plastic pipe is very smooth, and the C value of 150 is recommended for smooth pipes in Hazen-Williams tables.

The Hazen-Williams formula was developed from study of water distribution systems that used 3-in. or larger diameter pipes and discharges greater than 50 gpm. Under these flow conditions, the Reynolds number (N_R) is greater than 5×10^4, and the formula predicts friction loss satisfactorily.

However, for the smaller pipe, such as the typical ½-in. lateral hoses used in trickle irrigation systems, the Hazen-Williams formula with C = 150 underestimates the friction losses by about 30 percent. This phenomenon is demonstrated by figure 7–30, which shows laboratory test results for plain ½-in. trickle hose (0.58-in. ID) superimposed on the Moody diagram. The N_R for 70°F water flowing through a pipe can be computed by equation 7–45.

$$N_R = 3{,}214 \frac{Q}{D} \qquad \textbf{(7–45)}$$

The Darcy-Weisbach friction factor (f) in the Moody diagram is related to h_f by the Darcy-Weisbach formula, equation 7–46.

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \qquad \textbf{(7–46)}$$

Where

v = velocity of flow in the pipe, feet per second.

g = acceleration of gravity (32.2 ft/s²).

The "smooth pipe" line on the Moody diagram is generally considered the ultimate in pipe smoothness. For comparison, the "equivalent" f values for Hazen-Williams C values of 130, 140, and 150 are plotted on figure 7–30. The position of the C-value lines clearly shows a discrepancy in the "smooth pipe" concept in this range of Reynolds numbers. The C = 150 line, which represents Hazen-Williams smooth pipes, is well below the friction factor of

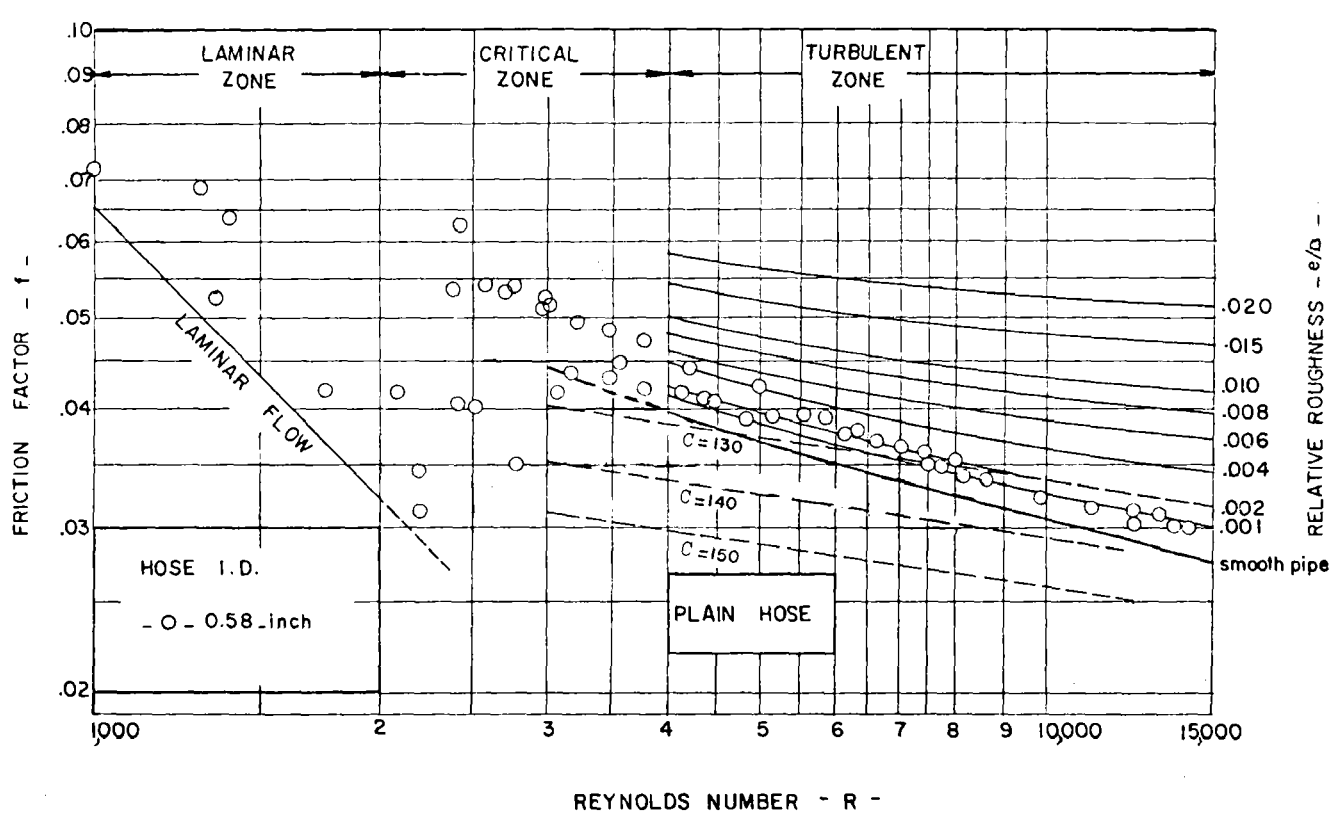


Figure 7–30.—Darcy-Weisbach f values for 1/2-in. (0.58-in. inside diameter) trickle irrigation hose.

Darcy-Weisbach smooth pipes. The range of Reynolds numbers shown represents hose discharge rates between 0.2 gpm and 3.0 gpm for ½-in. hose. The ½-in. hose exhibits characteristics somewhat above the Moody "smooth pipe" line and equivalent to an average C value of about 130. Note that the data points fall on lines generally parallel to the lines on the Moody diagram rather than on constant C-value lines. This observation strongly supports the conclusion that the Darcy-Weisbach formula represents the friction losses in hoses better than does the Hazen-Williams formula.

Pipe friction loss tables.—Tables of friction loss encountered in the common sizes of lateral hose and PVC thermoplastic pipe used for trickle irrigation systems are presented in Appendix B. These tables of pipe friction loss are based on the Darcy-Weisbach formulas and assume smooth pipe. The need for time-consuming interpolation is reduced by using small flow increments. The PVC pipes presented are for the lowest standard dimension ratio (SDR) (or pressure rating) iron pipe sizes (IPS) presented in the SCS standard for "Irrigation Water Conveyance Pipeline."[4] The friction tables were developed by computer, using equations 7–47a and 7–47b to compute f.

For $N_R < 2{,}000$:

$$f = \frac{64}{N_R} \qquad \textbf{(7–47a)}$$

and for $N_R \geq 2{,}000$:

$$\frac{1}{\sqrt{f}} = 0.80 + 2.0 \log (N_R \sqrt{f}) \qquad \textbf{(7–47b)}$$

Friction loss computations.—Equation 7–47b is quite tedious to use for desk computation of friction losses. The Blasius formula (equation 7–48), accounts for the low range in N_R in trickle irrigation systems. Equation 7–48 can be used for computing friction losses for N_R between 2,000 and 100,000.

$$f = 0.32\, N_R^{-0.25} \qquad \textbf{(7–48)}$$

The computation of J may be simplified by combining equation 7–45, 7–46, and 7–48 and adjusting the constant for average conditions. Equation 7–49a can be used to compute J for 5-in.-diameter or smaller plastic pipes and hoses. For D < 5 in.:

$$J = \frac{h_f 100}{L} = 0.133 \frac{Q^{1.75}}{D^{4.75}} \qquad \textbf{(7–49a)}$$

Equation 7–49b can be used to compute J for larger diameter plastic pipe. For D > 5 in.:

$$J = \frac{h_f 100}{L} = 0.100 \frac{Q^{1.83}}{D^{4.83}} \qquad \textbf{(7–49b)}$$

Equations 7–49a and 7–49b are as easy to use as the Hazen-Williams formula, and they more accurately predict friction loss for 70°F water flowing in smooth plastic pipe.

Head Losses Through Fittings

Equation 7–49 is developed for smooth plastic pipe without fittings. The three conventional methods for computing the additional pressure-head losses from special equipment, valves, and pipe and fittings are: (1) graphing friction loss vs. flow rate, (2) expressing the added pressure-head loss as the length of pipe (of the same diameter) that would give the same loss, and (3) expressing the loss in terms of a velocity head coefficient. Equation 7–50 can be used for computing friction head loss caused by a specific fitting (h_e), feet.

$$h_e = K_f \frac{V^2}{2g} \qquad \textbf{(7–50)}$$

Where

K_f = friction head-loss coefficient for a specific fitting.

$V^2/2g$ = velocity head, which is the energy head from the velocity of flow, feet.

Graphs, equivalent lengths, or K_f values should be supplied by manufacturers or taken from handbooks on hydraulics. Usually the losses attributed to standard pipe fittings are small and can be grouped in a miscellaneous friction-loss safety factor as shown under Samples of Trickle Irrigation System Designs, Drip System.

Emitter-connection loss equivalent lengths (f_e), feet, representing losses for different barb sizes and lateral diameters are shown in figure 7–23, which

[4]Soil Conservation Service, U.S. Dep. Agric. 1977–81. National Handbook of Conservation Practices.

should be used when the manufacturer does not provide emitter-connection loss data. For computing the friction head loss, the equivalent length of the lateral with emitters (l'), feet, can be computed by equation 7–51a and substituted for the actual length of the lateral with emitters (l), feet.

$$l' = l\left(\frac{S_e + f_e}{S_e}\right) \qquad \textbf{(7–51a)}$$

Where

S_e = spacing between emitters on the lateral, feet.

In graphic analysis of lateral head loss, increasing the equivalent head-loss gradient of the lateral with emitters (J') is a convenient way to account for the emitter connection roughness, and J', feet per 100 feet, can be computed by equation 7–51b.

$$J' = J\left(\frac{S_e + f_e}{S_e}\right) \qquad \textbf{(7–51b)}$$

Where

J = head loss gradient of the lateral with emitters, feet per 100 feet.

Multiple-Outlet Pipeline Losses

Head loss from pipe friction (h_f) in laterals and manifolds that have evenly spaced outlets and uniform discharge from each outlet can be estimated by equation 7–52.

$$h_f = J'FL/100 \qquad \textbf{(7–52)}$$

Where

J' = equivalent head-loss gradient of the lateral with emitters, feet per 100 feet.
F = reduction coefficient to compensate for the discharge along the pipe.
L = pipe length, feet.

Table 7–6 gives F values for various numbers of openings along the pipe. The F values are given for use with both the Hazen-Williams formula (flow rate exponent 1.85) and the Darcy-Weisbach tables or equation 7–49a (flow rate exponent 1.75). The F values were computed by dividing the actual computed loss in multiple-outlet pipelines (with equal discharge per outlet) by the head loss in pipelines of equal diameter and length but with only one outlet.

Dimensionless Pipe-Friction Curve

The head loss along any multiple outlet pipeline that has uniform outlet spacing and discharge can be represented by a single line as a dimensionless plot. Figure 7–31 shows such a plot when the horizontal scale is a dimensionless ratio of any position (x), feet, along the length divided by the total length of the multiple-outlet pipeline (L), feet. The vertical axis represents the head loss from pipe friction (h_f), feet, divided by L/100. This general friction curve can be adapted to a specific problem by setting the intercept of the friction curve (at x/L = 1.0) equal to J'F for a specific lateral or manifold pipe diameter, flow rate, number of outlets, and length.

Table 7–6.—Reduction coefficient (F) for multiple-outlet pipeline friction-loss computations in which the first outlet is a full spacing from the pipe inlet

Number of outlets	F		Number of outlets	F	
	1.85[1]	1.75[2]		1.85[1]	1.75[2]
1	1.00	1.00	9	0.41	0.42
2	0.64	0.65	10–11	0.40	0.41
3	0.54	0.55	12–15	0.39	0.40
4	0.49	0.50	16–20	0.38	0.39
5	0.46	0.47	21–30	0.37	0.38
6	0.44	0.45	31–70	0.36	0.37
7	0.43	0.44	>70	0.36	0.36
8	0.42	0.43			

[1]The flow rate exponent of 1.85 is for use with the Hazen-Williams formula.
[2]The flow rate exponent of 1.75 is for use with tables based on the Darcy-Weisbach equation and smooth-pipe curve on the Moody diagram or with equation 7–49a.

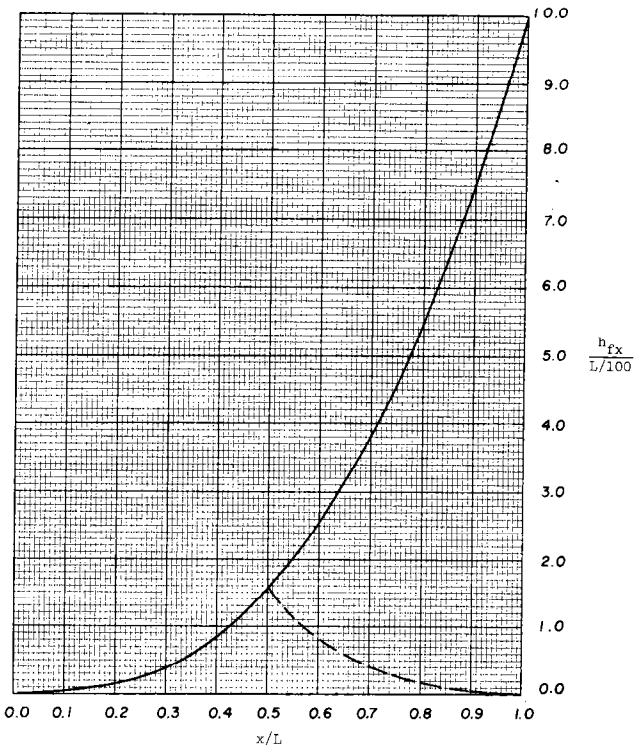


Figure 7–31.—General friction curve for a multioutlet pipeline that has uniform diameter, uniform spacing between outlets, and uniform flow per outlet. X = any position along the length, feet; L = total length, feet; h_{fx} = head loss from position x to the closed end, feet.

The shape of the general friction curve can be plotted from an outlet-by-outlet analysis of a typical multiple-outlet line. It can also be determined mathematically by equation 7–53.

$$\frac{h_{fx}}{L/100} = J'F\left(\frac{x}{L}\right)^{2.75} \qquad \textbf{(7–53)}$$

Where

h_{fx} = head loss from position x to the closed end, feet.
J' = equivalent head-loss gradient of the pipe with emitters, feet per 100 feet.
F = reduction coefficient to compensate for the discharge along the pipe.
x = distance from the closed end, feet.

Equation 7–53 can be derived mathematically by first combining equations 7–49a, 7–51b, and 7–52 to obtain:

$$h_f = \frac{L}{100} F \left(\frac{S_e + f_e}{S_e}\right) 0.133 \frac{Q^{1.75}}{D^{4.75}}$$

Where

h_f = head loss from pipe friction, feet.
S_e = spacing between emitters on a lateral, feet.
f_e = emitter-connection loss equivalent length, feet.
Q = flow rate in the pipe, gallons per minute.
D = ID of the pipe, inches.

Then L is replaced with x and Q with Qx/L to obtain the h_{fx} at any point x from the closed end, and both sides are divided by L to obtain the dimensionless expression:

$$\frac{100h_{fx}}{L} = \frac{x}{L} F \left(\frac{S_e + f_e}{S_e}\right) 0.133 \frac{[(x/L)Q]^{1.75}}{D^{4.75}}$$

Equation 7–53 can now be obtained by combining terms and noting that:

$$J' = \frac{S_e + f_e}{S_e} 0.133 \frac{Q^{1.75}}{D^{4.75}}$$

The mathematical derivation of equation 7–53 assumes that F is a constant between the end and any point in the multiple-outlet pipeline. This assumption is obviously not true, but on pipelines that have 12 or more outlets the error is less than 5 percent.

Equation 7–53 can also be derived graphically from a plot of x/L vs. $h_{fx}/(L/100)$ data obtained from an outlet-by-outlet analysis of a multiple-outlet pipeline. Table 7–7 gives a set of data developed from a hydraulic analysis of multiple-outlet pipeline. The dimensionless friction-loss values have been adjusted so that 100 H_{fx}/L = 10.00 at x/L = 1.0. These data are useful for plotting curves such as figure 7–31 with different scales.

Economic Pipe-Size Selection

The economics of trickle irrigation is very important to management in modern agriculture. The essence of economic selection of pipe size for a main line is to find the minimum sum of fixed costs plus operating costs on either a present-worth or an an-

Table 7-7.—Dimensionless data for plotting friction curves for multiple-outlet pipelines[1]

x/L	100 h_{fx}/L	x/L	100 h_{fx}/L
0.10	0.02	0.60	2.45
0.20	0.13	0.65	3.05
0.25	0.23	0.70	3.74
0.30	0.37	0.75	4.52
0.35	0.57	0.80	5.40
0.40	0.81	0.85	6.38
0.45	1.12	0.90	7.47
0.50	1.49	0.95	8.68
0.55	1.93	1.00	10.00

[1]x = distance from the closed end, feet; L = length of the multiple-outlet pipeline, feet; h_{fx} = head loss from position x to the closed end, feet.

nual basis as presented pictorially in figure 7-32. Usually it is sufficient to represent this sum by the cost of the pipe in place and the energy cost (in terms of the fuel required by the pumping plant) of pressure lost in pipe friction.

Although the selection of economical pipe sizes is an important engineering decision, it is often given insufficient attention, especially in designing relatively simple irrigation systems, because the methods of selection are considered too time consuming, limited, or complex. The economic pipe-size selection chart (fig. 7-33) was developed to simplify the pipe-sizing process for manifolds and main lines for PVC pipe with lowest SDR (or pressure rating) IPS pipe sizes.

Life-Expectancy Costs

To determine the most economical life-expectancy cost of a system, find the minimum fixed-plus-operating costs. Visualize the problem by thinking of selecting the diameter of a water supply line. If a very small pipe is used the initial cost will be low, but the operating (energy-for-power) cost for overcoming friction losses in the pipe will be large. As the pipe diameter increases, the fixed costs increase, but the power costs decrease. The optimum pipe size, where the sum of the fixed costs plus power costs is at a minimum, is illustrated in figure 7-32.

The concept of value engineering represented by figure 7-32 can be used for the life-expectancy costs of more complex systems by taking into account all of the potential fixed costs such as various types of basic hardware, land preparation, mechanical additions, and automation. These fixed costs can then be added to the full set of operating costs, including energy, labor, maintenance, and management.

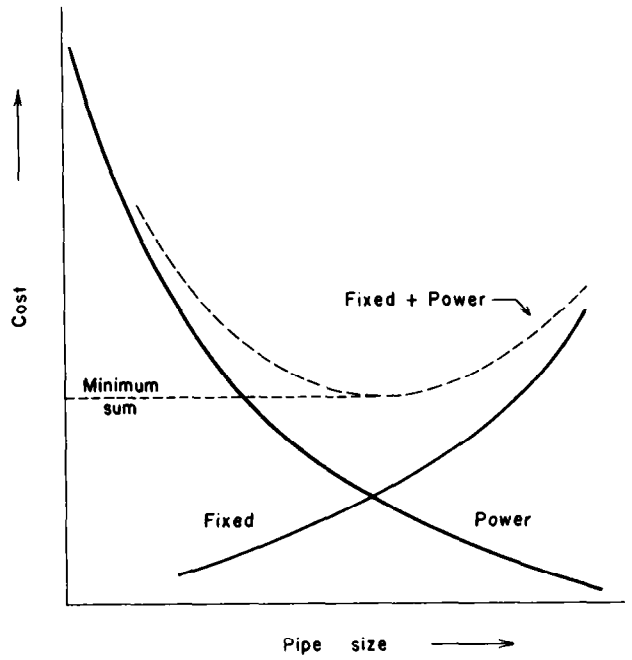


Figure 7-32.—Influence of pipe size on fixed, power, and total costs.

The life-expectancy cost can be analyzed on a capital value or on an annual value. In either analysis the interest rate (i), the expected life of the item (n), and the estimated annual rate of increase in energy costs (r) must be considered. Table 7-8 lists the necessary factors for either a present-worth or an annual life-expectancy cost analysis, assuming a 9-percent annual rise in energy costs, for 10- to 25-percent interest rates and 7- to 40-year life expectancies.

The present worth factor of the rising energy cost [PW(r)] and the equivalent annual factor of the rising energy cost [EAE(r)] were computed by equations 7-54 and 7-55 for $r \neq i$.

$$PW(r) = \left[\frac{(1+r)^n - (1+i)^n}{(1+r) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right] \quad \textbf{(7-54)}$$

and

$$EAE(r) = \left[\frac{(1+r)^n - (1+i)^n}{(1+r) - (1+i)}\right] \times \left[\frac{i}{(1+i)^n - 1}\right] \quad \textbf{(7-55)}$$

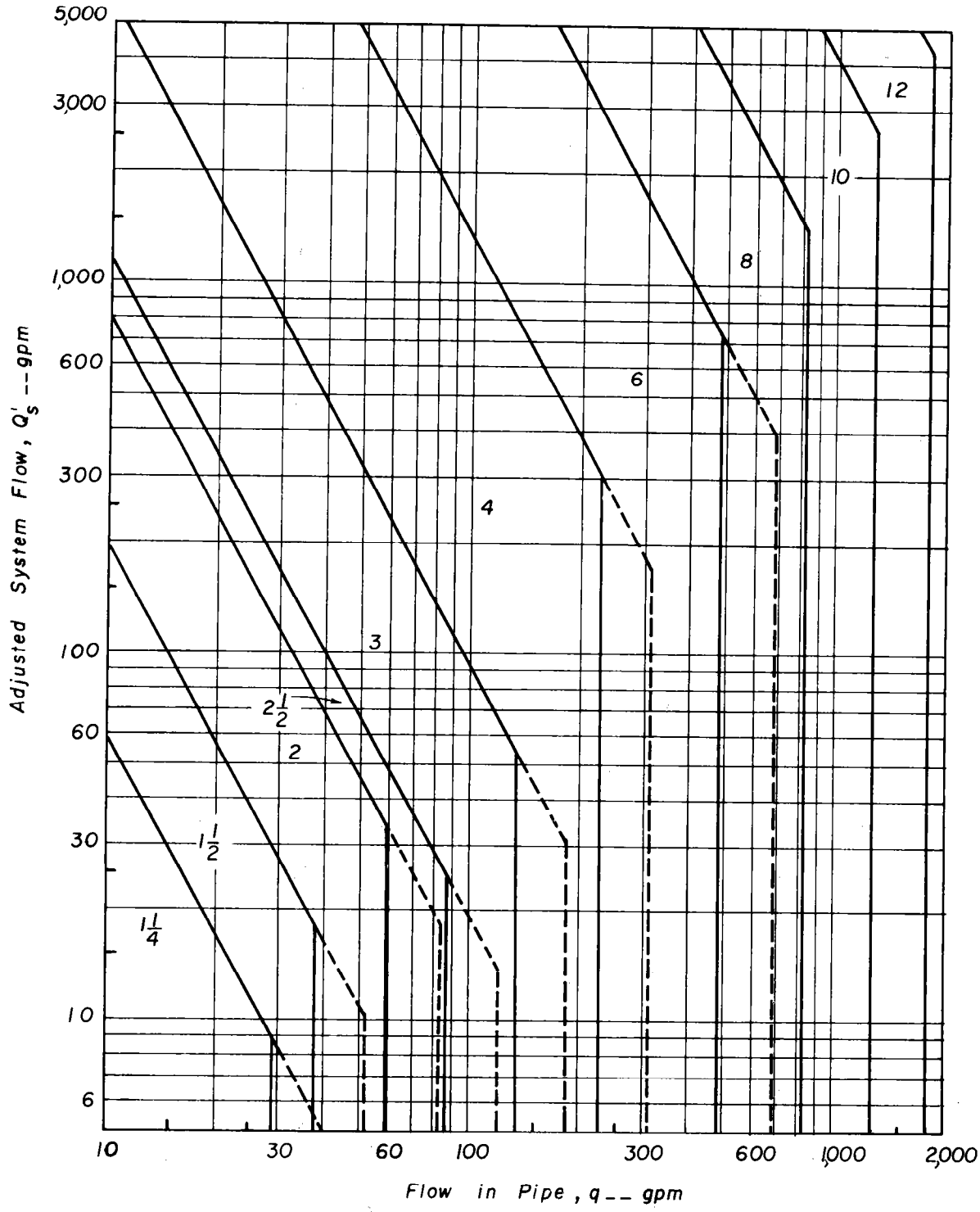


Figure 7–33.—Economic pipe-size selection chart for polyvinyl chloride thermoplastic IPS (iron pipe size) pipe having minimum acceptable SDR (standard dimension ratio) ratings. (Solid and dashed vertical lines, respectively, represent 5 to 7 ft/s velocity limitations.)

Table 7–8.—Present-worth and annual economic factors for an assumed 9-percent annual rise in energy costs with various interest rates and life expectancies

Interest (i), %[1]	Factor	Factor value with indicated life expectancy (n), years					
		7	10	15	20	30	40
10	PW(9%)[2]	6.193	8.728	12.802	16.694	23.964	30.601
	EAE(9%)[3]	1.272	1.420	1.683	1.961	2.542	3.129
	CRF[4]	0.205	0.163	0.132	0.118	0.106	0.102
	PW(0%)[5]	4.868	6.145	7.606	8.514	9.427	9.779
15	PW(9%)	5.213	6.914	9.206	10.960	13.327	14.712
	EAE(9%)	1.253	1.378	1.574	1.751	2.030	2.215
	CRF	0.240	0.199	0.171	0.160	0.152	0.151
	PW(0%)	4.160	5.019	5.848	6.259	6.566	6.642
20	PW(9%)	4.453	5.615	6.942	7.762	8.583	8.897
	EAE(9%)	1.235	1.339	1.485	1.594	1.724	1.781
	CRF	0.277	0.239	0.214	0.205	0.201	0.200
	PW(0%)	3.605	4.193	4.676	4.870	4.979	4.997
25	PW(9%)	3.854	4.661	5.449	5.846	6.147	6.224
	EAE(9%)	1.219	1.306	1.412	1.479	1.539	1.556
	CRF	0.316	0.280	0.259	0.253	0.250	0.250
	PW(0%)	3.161	3.571	3.859	3.954	3.995	4.000

[1]Interest is the time value of unsecured money to the developer.
[2]PW(9%) is the present-worth factor of the rising cost of energy, taking into account the time value of money over the life expectancy.
[3]EAE(9%) is the equivalent annual factor of the rising cost of energy, taking into account the time value of money over the life expectancy.
[4]CRF is the uniform-series annual payment (capital recovery factor), taking into account the time value of money and the depreciation of equipment over the life expectancy.
[5]PW(0%) is the present-worth factor of the constant cost of energy, taking into account the time value of money over the life expectancy.

The standard capital-recovery factor (CRF) was computed by equation 7–56.

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1} \qquad \textbf{(7–56)}$$

In the consideration of life-expectancy cost, the time value of unsecured money to the developer should be used as the appropriate i value in equations 7–54, 7–55, and 7–56. This rate is normally higher than bank interest rates because of the higher risks involved. For unsecured agricultural developments, the interest rates of high-grade, long-term securities should be doubled unless special tax benefits are involved.

The n of properly designed and installed PVC pipe should be 40 years. However, because of obsolescence, n values of 20 or less are frequently used. The number of brake horsepower (BHP) hours per unit of fuel that can be expected from efficient power units is as follows:

Diesel fuel	15.0 BHP hr/U.S. gal
Gasoline (water cooled)	10.5 BHP hr/U.S. gal
Tractor fuel	8.5 BHP hr/U.S. gal
Butane-propane	9.5 BHP hr/U.S. gal
Natural gas	8.5 BHP hr/100 ft^3
Electricity	1.2 BHP hr/kWh @ meter

From table 7–8 some interesting observations can be made concerning the long-term effects of rising energy costs:

1. Low i values deemphasize high first costs, as indicated by low CRF's.
2. Low i values emphasize rising energy costs, as indicated by high PW(9%)'s and EAE(9%)'s, but have less effect on constant energy costs, as indicated by PW(0%)'s.
3. High i values emphasize high first costs, but deemphasize energy costs.
4. Long useful life deemphasizes high first costs, but emphasizes energy costs.
5. Rising energy costs have a maximum effect when i is low and n is high.

6. The relative effect of rising vs. constant energy costs can be observed by comparing PW(9%) to PW(0%) or EAE(9%) to EAE(0%) = 1.0 for any n and i.

The factors presented in table 7–8 can be used with the present annual power costs (E) and the cost of the irrigation system (C) to estimate the following:

1. The present worth of the rising (9 percent per year) annual energy cost, E × PW(9%).
2. The equivalent annual cost (E′) of the rising (9 percent per year) energy cost, E × EAE(9%).
3. The annual fixed cost of the irrigation system, C × CRF.
4. The present worth of the constant energy cost, E × PW(0%).
5. The annual cost of the constant energy cost, E.
6. The present worth of the irrigation system, C.

Economic Pipe-Selection Charts

Development.—Figure 7–33 was developed for PVC thermoplastic pipe with the lowest SDR (or pressure rating) IPS pipe sizes presented in the SCS Standard "Irrigation Water Conveyance Pipeline." (These are the same pipe sizes for which friction loss tables are presented in Appendix B.) The chart can be adjusted for a given set of economic conditions and entered to directly select the most economical pipe sizes for nonlooping systems with a single pump station. The following example demonstrates how the chart is constructed, so that charts for PVC pipe of other sizes or wall thicknesses can be developed.

Step 1—Assume: cost recovery factor (CRF) = 0.100; cost per water horsepower per year (C_{whp}) = \$100.00; and PVC pipe cost = \$1.00/lb. Obtain the ID and weight per foot of pipe of each size being considered. This example shows construction of the line separating the 3- and 4-in. regions.

The ID and weight of 3-in. SDR 32.5 pipe are 3.284 in. and 74.2 lb/100 ft, respectively, and those of 4-in. SDR 41 pipe are 4.280 in. and 98.4 lb/100 ft, respectively.

Step 2—Determine the yearly fixed-cost differences between adjacent 3- and 4-in. pipes with CRF = 0.100:

$$0.100(\$98.4 - \$74.2) = \$2.42/100 \text{ ft}$$

Step 3—Determine the water horsepower savings needed to offset the annual fixed-cost difference between adjacent 3- and 4-in. pipes with C_{whp} = \$100.00:

$$\frac{\$2.42/100 \text{ ft}}{\$100.00} = 0.0242 \text{ whp/100 ft}$$

Step 4—Assume a convenient system flow rate (Q_s') and compute the difference in head loss between the adjacent pipe of different sizes ($h_{f(a,b)}$) needed to obtain the water horsepower savings computed in step 3. Assuming a Q_s' of 100 gpm for the 3- and 4-in. pipe sizes:

$$h_{f(3,4)} = \frac{0.0242 \text{ whp/100 ft} \times 3{,}960}{100 \text{ gpm}}$$

$$= 0.958 \text{ ft/100 ft}$$

Step 5—Determine the rate of pipe flow that will produce the required $h_{f(a,b)}$ between adjacent pipe of different sizes. These flow rates can be determined by trial and error with head loss gradient (J) values from calculation of pipe friction loss or from tables of friction losses. Using the friction loss tables in Appendix B for the 3- and 4-in. pipe at emitter discharge (q) = 95 gpm:

$$J_{(a,b)} = J_{(a)} - J_{(b)}$$

$$J_{(3,4)} = 1.34 - 0.38 = 0.96 \text{ ft/100 ft}$$

Step 6—Plot the points representing the Q_s' used in step 4 and q found in step 5 on log-log graph paper as in figure 7–33. For the 3- and 4-in. PVC pipes in this example, the point is Q_s' = 100 gpm and q = 95 gpm.

Step 7—Draw a line with a slope of −1.80 through each of the points plotted in step 6. These lines represent the set of q values that give the same fixed-plus-operating cost with adjacent sizes of pipe for various Q values. Each pair of lines defines the region in which the pipe size common to both lines is the most economical size to use.

Step 8—Draw a set of vertical lines that represent the q that would give a velocity of 5 ft/s for each pipe size. For the 3-in. pipe this is 132 gpm (see Appendix B), which is represented by the solid vertical line separating regions 3 and 4 of figure 7–33. Since velocity restrictions override eco-

nomic considerations, the vertical line defines the boundary between the 3- and 4-in. pipe regions at a flow rate of 132 gpm. (The dashed extensions are for velocities of 7 ft/s.)

The economic pipe-selection chart for PVC thermoplastic IPS pipe with minimum acceptable SDR rating (fig. 7–33) is based on pipe cost at \$1.00/lb, C_{whp} = \$100.00, and CRF = 0.100. The negative-sloping lines represent all the possible Q-vs.-q values for each of the adjacent pairs of pipe sizes that will give the same sum of fixed costs plus operational costs. The zone between adjacent lines defines the region of Q-vs.-q values when the pipe size that is common to both lines is the most economical selection. Figure 7–33 is universally applicable for the most economical selections of pipe size in any sized series system for the economic boundary conditions used. Uses of this chart for manifold and main-line design are presented for drip and spray systems under Sample Design for Trickle Irrigation Systems.

To use figure 7–33 for a system with various economic factors, the total system capacity (Q_s) must be adjusted to compensate for various C_{whp} and CRF values. To do this, first compute the C_{whp} by equation 7–57.

$$C_{whp} = \frac{(Q_t)(P_{uc})[EAE(r)]}{(E_p)(BHP/P_u)} \qquad (7\text{–}57)$$

Where

Q_t = average pump operating time per season, hours, equation 7–37.
EAE(r) = the equivalent annual cost factor of the rising energy cost, taking into account the time value of money and depreciation of equipment over the life expectancy, table 7–8 or equation 7–55.
P_{uc} = unit cost of power, dollars per kilowatt-hour.
E_p = pump efficiency.
BHP = brake horsepower.
P_u = unit of power.

Next, determine the system flow-rate adjustment factor (A_f) by equation 7–58.

$$A_f = \frac{0.001C_{whp}}{(CRF)(P_c)} \qquad (7\text{–}58)$$

Where

CRF = capital recovery factor, table 7–8 or equation 7–56.
P_c = pipe cost, dollars per pound.

The system flow rate for entering the economic chart (Q_s'), gallons per minute, is computed by equation 7–59.

$$Q_s' = A_f Q_s \qquad (7\text{–}59)$$

Where

Q_s = system flow rate under consideration, gallons per minute.

The constant 0.001 in equation 7–58 is the number that gives $A_f = 1$ with the economic factors used in developing figure 7–32. For economic pipe-size selection charts developed from other economic factors, the constant must be changed so that $A_f = 1$ for the C_{whp}, CRF, and pipe cost/unit used.

The procedure using the economic design chart and main-line design strategy as presented under Sample Designs for Trickle Irrigation Systems, Drip System, involves the following:

Step 1—Enter the vertical axis of figure 7–33 with Q_s' and select an "economic pipe size" for the q in each section of main-line pipe. (To hold velocities below 5 ft/s, stay within the solid vertical boundary lines.)

Step 2—Determine the head loss from pipe friction (h_f) in each section of pipe by equation 7–49a or 7–49b or from the pipe friction tables, Appendix B.

Step 3—Compute the pressure head required to overcome pipe friction plus elevation difference between the pump and each manifold inlet at m[$(H_{fe})_m$], feet, by equation 7–60.

$$(H_{fe})_m = \sum_{1}^{m} h_f \pm \triangle El \qquad (7\text{–}60)$$

Where

$\sum_{1}^{m} h_f$ = sum of the pipe friction losses between the pump and manifold inlet at m, feet.
$\triangle El$ = difference in elevation between the pump and manifold m (+ is uphill

to manfold and − is downhill), feet.

Step 4—Once the $(H_{fe})_m$ has been determined for the critical manifold, the size of other main-line branches can often be reduced. Other prospects for reduction are sections of main line that connect points that are downstream and have lower elevations than the critical manifold. The exact length of the smaller diameter pipe that will increase the head loss between two points by a specified amount (L_s), feet, can be computed by equation 7–61.

$$L_s = \frac{\triangle H}{J_s - J_l} \times 100 \qquad \textbf{(7–61)}$$

Where

$\triangle H$ = desired pressure-head increase between two points, feet.
J_s = head loss gradient of the smaller pipe, feet per 100 feet.
J_l = head loss gradient of the larger pipe, feet per 100 feet.

Lateral Line Design

This section presents the procedures for determining lateral characteristics such as: (1) flow rate and inlet pressure, (2) location and spacing of the manifolds that in effect set the lateral lengths, and (3) estimated differences in pressure within laterals.

On fields where the average slope along the laterals is less than 3 percent, it is usually most economical to supply laterals to both sides of each manifold. The manifold should be positioned so that, starting from a common manifold connection, the minimum pressures in the pair of laterals (one to either side of the manifold) are equal. Thus, on level ground the pair of laterals should have equal lengths (l) and the manifold spacing $(S_m) = 2l = L$.

If the ground slopes along the laterals (rows), the manifold should be shifted uphill from the center line. The effect is to shorten the upslope lateral and lengthen the downslope lateral so that the combination of pipe friction loss and elevation difference is in balance. The amount of the shift can be determined either graphically or numerically.

The spacing of manifolds is a compromise between field geometry and lateral hydraulics. As practical limits for preliminary design purposes, lateral pressure-head differences ($\triangle h$) can be limited to one-half of the allowable subunit pressure-head variations ($0.5\ \triangle H_s$) where the manifold plus attached laterals make up a subunit. The $\triangle h$ for a given S_m and set of lateral specifications is about the same for laterals on level fields as for laterals with slopes of as much as 2 percent. This observation helps in computing the S_m and in designing the layout of the pipeline network. For simplification, the design procedure is based on laterals that have an average emitter flow rate (q_a).

Characteristics

Several general characteristics of laterals are important to the designer.

Length.—When two laterals extend in opposite directions from a common inlet point on a manifold, they are referred to as a *pair of laterals.* For example, the laterals in figure 7–27 are paired. The length of a pair of laterals (L) is equal to the manifold spacing (S_m). The length of a *single lateral* that extends in only one direction from a manifold is designated by l.

Flow rate.—The flow rate of a lateral (q_l), gallons per minute, can be computed by equation 7–62.

$$q_l = \frac{l}{S_e}\frac{q_a}{60} = \frac{n_e q_a}{60} \qquad \textbf{(7–62)}$$

Where

S_e = spacing of emitters on the lateral, feet.
n_e = number of emitters along the lateral.
q_a = average emitter flow rate, gallons per hour.

Inlet pressure.—Sometimes it is useful to know the inlet pressure required by the average lateral in a system. The average emitter pressure head (h_a) is computed as the head that will give q_a. The general location of the average emitter that yields q_a at h_a is between $x/L = 0.60$ and $x/L = 0.62$ for constant-diameter laterals. Furthermore, about three-fourths of the head loss occurs between the average emitter and the inlet, where the flow is greatest. As flow in the lateral decreases because of water being discharged through the emitters, the head loss curve flattens (see fig. 7–31) so that only about one-fourth of the total loss takes place between the average emitters and the end.

Data in table 7–7 demonstrate the above as follows:

1. The average value of 100 h_{fx}/L is 2.67 when end effects and the values at x/L = 0.05 and 0.15 (which are not included in table 7–7) are accounted for.

2. The location of 100 $h_{fx}/L = 2.67$ can be determined by letting the friction gradient (JF) = 10.00 (which is the value used in generating table 7–7) and solving to obtain:

$$\frac{x}{L} = \left(\frac{2.67}{10.00}\right)^{1/2.75} = 0.62$$

3. The portion of the total friction loss between x/L = 0.62 and the closed end is 2.67/10.00 or about one-fourth.

The inlet pressure head that will give h_a (h_l), feet, for a pair of constant-diameter laterals with $L = S_m$ laid on a uniform slope can be computed by equations 7–63a and 7–63b.

$$h_l = h_a + 0.75h_{fp}[z^{3.75} + (1 - z)^{3.75}] - \frac{\triangle El}{2}(2z - 1) \qquad \textbf{(7–63a)}$$

Where

h_{fp} = friction loss in a lateral with length L, feet.

z = location of the inlet to the pair of laterals that gives equal minimum pressures in both uphill and downhill members (expressed as the ratio of the length of the downhill lateral to L.)

$\triangle El$ = absolute difference in elevation between the two ends of the pair of laterals, feet.

For level fields this reduces to:

$$h_l = h_a + 0.75h_{fp}(0.5)^{2.75} = h_a + 0.11h_{fp} \qquad \textbf{(7–63b)}$$

For a single constant-diameter lateral laid on uniform slopes, h_l can be computed by equation 7–63c,

$$h_l = h_a + \frac{3h_f}{4} + \frac{\triangle El}{2} \qquad \textbf{(7–63c)}$$

and the pressure head at the closed end of the lateral (h_c), feet, can be computed by equation 7–64a or 7–64b.

$$h_c = h_a - \left(\frac{h_f}{4} + \frac{\triangle El}{2}\right) \qquad \textbf{(7–64a)}$$

$$h_c = h_l - (h_f + \triangle El) \qquad \textbf{(7–64b)}$$

Where

h_f = head loss from pipe friction, feet.

$\triangle El$ = change in elevation (+ for laterals running uphill from the inlet and – for laterals running downhill, feet).

Tapered laterals.—Usually, constant-diameter laterals are used, because they are convenient to install and maintain, but tapered laterals may be less expensive. Tapered laterals are sometimes used on steep slopes where the increase in pressure from the slope would result in too much pressure at the end.

If a lateral were tapered so that the friction loss per unit length were uniform throughout, the average pressure would occur at the midpoint. In such a lateral, the term $3h_f/4$ in equation 7–63c would be changed to $h_f/2$. It is impractical to use more than two pipe sizes; therefore, when calculating h_l for a tapered lateral, replace $3h_f/4$ with $2h_f/3$ in equation 7–63c. When computing h_c by equation 7–64a, replace $h_f/4$ with $h_f/3$.

For tapered laterals, h_f must be computed in a three-step process:

Step 1—Compute h_f by equation 7–52 for the full length of the lateral that has the larger diameter pipe.

Step 2—Compute h_f values for both the large- and the small-diameter pipes for a lateral length equal to the length of small-diameter pipe and determine the difference between these values.

Step 3—The h_f for the tapered lateral will equal the h_f found in step 1 plus the difference in the two h_f values found in step 2.

In computing h_f for tapered laterals, all the computations involving equation 7–52 (and those using monographs or slide rule calculators) must include the closed end of the lateral or manifold. This must be done because use of the reduction coefficient (F) involves the assumption that (1) the discharges from all outlets are equal, and (2) no water flows beyond the last outlet of the pipe section being considered. For further details on design of multioutlet pipeline, refer to Manifold Design.

Spacing of Manifolds

The manifold spacing (S_m) in orchards should be such that adjacent manifolds are a whole number of tree spacings (S_p) apart. Furthermore, it is most convenient to have the same S_m throughout the field in all crops. A detailed example is presented under Drip System in Sample Designs for Trickle Irrigation Systems. The procedure is as follows:

Step 1—Inspect the field layout and select a reasonable S_m in accordance with the criteria listed above.

Step 2—Determine the lateral pipe friction loss (h_f) with laterals half as long as S_m (eq. 7–51 and 7–52).

Step 3—Assume that h_f = the pressure head difference along the lateral ($\triangle h$), i.e., the field is level, and compare the latter with 0.5 times the allowable subunit pressure-head variation ($\triangle H_s$) (eq. 7–34). If $\triangle h$ is much larger than 0.5 $\triangle H_s$, S_m should be decreased. If it is much smaller, S_m may be increased.

Once the friction loss for a given length of lateral has been computed, the friction loss for any other length of lateral can be computed by equation 7–65a, which is a rearrangement of equation 7–53.

$$(h_f)_b \cong (h_f)_a \left(\frac{l_b}{l_a}\right)^{2.75} \qquad \textbf{(7–65a)}$$

Where

l_a and l_b = original and new lateral pipe length, feet.

$(h_f)_a$ and $(h_f)_b$ = original and new lateral pipe friction losses, feet.

Conversely, the length of lateral (l_b) that will give any desired $(h_f)_b$ can be computed by equation 7–65b.

$$l_b \cong l_a \left(\frac{(h_f)_b}{(h_f)_a}\right)^{1/2.75} \qquad \textbf{(7–65b)}$$

Location of Manifolds

As discussed earlier, on level fields laterals should extend an equal length (l) to either side of the manifolds so that l = half the manifold spacing ($S_m/2$). On sloped fields the manifolds should be shifted uphill from the center line of the subunits, as shown in figure 7–9. The location of the manifold that will give the same minimum and maximum pressures in the uphill and downhill laterals can be determined either graphically or numerically.

Graphical solution.—The graphical solution is based on the general friction curve, figure 7–31. A detailed example of the graphical determination is presented under Drip System in Sample Designs for Trickle Irrigation Systems. The procedure is as follows:

Step 1—Determine the equivalent head-loss gradient (J′), feet, and reduction coefficient to compensate for the discharge (F) for a single lateral equal in length to the S_m. (Note: this lateral will have twice the flow rate used in step 2 of the manifold-spacing procedure.)

Step 2—Place an overlay on figure 7–31 and trace the friction curve and horizontal boundaries. For use of the 0-to-10 dimensionless horizontal scale, values for specific problems must be multipled by 10/J′F, found in step 1.

Step 3—On the overlay, draw a line representing the ground surface such that (a) the line is tangent to the friction curve and (b) the drop in elevation or slope is properly scaled.

Step 4—Locate the best manifold positions by moving the overlay down until the dashed friction curve coincides with the ground line at manifold position (x/L) = 1.0. The dashed curve represents the uphill lateral, and the intersection between the two curves is the optimum manifold location for the given S_m and topography. (Note that the solid and dashed curves intersect at x/L = 0.5 on figure 7–31. This is obviously the optimum manifold location for a level field. The dashed curve is a mirror image of the x/L = 0 to 0.5 position of the solid friction curve.)

Step 5—Adjust the manifold location uphill by as much as 3/4 of the tree spacing (S_p) or downhill by as much as 1/4 S_p, so that it falls midway between tree spacings.

Step 6—Determine the maximum head variation along the pair of laterals ($\triangle h$), feet, by first determining the maximum distance the friction curves are above the ground surface line (which is equivalent to the scaled value of $\triangle h$ divided by L/100) and then determining $\triangle h$ by equation 7–66.

$$\triangle h = \frac{J'F}{10} \frac{L}{100} \left(\frac{\triangle h}{L/100}\right)' \qquad \textbf{(7–66)}$$

Where

L = S_m, feet.
$(100\,\triangle h/L)'$ = maximum scalar distance between the friction curve and the ground surface line in the graphical solution.

Numerical solution.—The numerical solution, based on equation 7–53 and presented under Drip System in Sample Designs for Trickle Irrigation Systems, follows the same logic and procedural steps as the graphical solution. Figure 7–34 shows the dimensionless terms used in the computation that follows.

Step 1—Determine J′ and F for a single lateral equal in length to S_m.

Step 2—Find the tangent location (Y) by equation 7–67 when the average slope of the ground line (S), percent, ≤ J′; when S > J′, Y = 1. This is the x/L where the friction curve is tangent to the ground, figure 7–34.

$$Y = (S/J')^{1/1.75} \qquad \textbf{(7–67)}$$

Step 3—Solve for the unusable slope component (S′) by equation 7–68. This is the amount the friction curve needs to be raised so that it does not dip below the ground line.

$$S' = SY - J'F(Y)^{2.75} \qquad \textbf{(7–68)}$$

Step 4—Determine the optimum x/L that satisfies equation 7–69.

$$\frac{S - S'}{J'F} = (x/L)^{2.75} - (1 - x/L)^{2.75} \qquad \textbf{(7–69)}$$

To satisfy the equation, first determine the quantity on the left, and then by trial and error find the appropriate x/L value that will satisfy it.

Step 5—Adjust the manifold to fall midway between two tree rows as in step 5 of the graphical solution.

Step 6—For laterals on relatively mild slopes, the maximum △h along the pair of laterals can be determined from the x/L value that represents the actual manifold location selected by equation 7–70.

$$\triangle h = \frac{L}{100}[J'F(x/L)^{2.75} + S' - S(x/L)] \qquad \textbf{(7–70)}$$

For steep slopes the maximum △h may occur at the closed end of the downstream lateral. To check for this possibility, determine the difference ($\triangle h_c$) between the downstream-end and minimum pressure heads by equation 7–71a or directly by equation 7–71b.

$$\triangle h_c = S'(L/100) \qquad \textbf{(7–71a)}$$

$$\triangle h_c = S^{1.57}(J')^{-0.57}(1 - F)L/100 \qquad \textbf{(7–71b)}$$

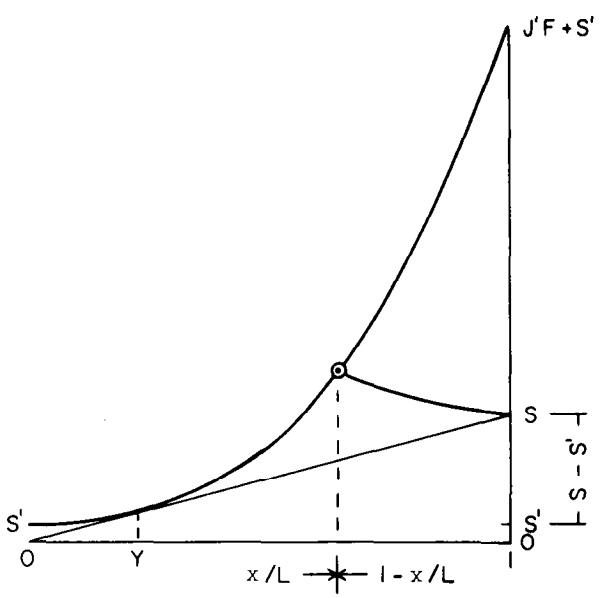


Figure 7–34.—Dimensionless sketch showing terms used in numerical solution of optimum position for manifold. J′F = friction gradient; S′ = average slope of the ground line; Y = tangent location; x/L = manifold position.

Pressure Difference

The pressure head difference (△h) along the laterals must be known for estimating the final emission uniformity (EU) of the system. As mentioned earlier, △h should be about 0.5 times the allowable subunit pressure-head variation ($\triangle H_s$) or less. Methods for computing △h are stated in step 6 of both the graphical and numerical solutions for manifold positioning (see above). However, for some designs the manifold placement is dictated by other considerations and △h must be determined by some other means.

For laterals on downhill slopes of less than 0.3

percent, level ground, or uphill slopes, $\triangle h$ can be assumed equal to the lateral inlet pressure head (h_l) minus the pressure head at the closed end (h_c) and equation 7–63 and 7–64 can be used to determine h_l and h_c. For steeper downhill laterals, equations 7–63 and 7–64 still are valid as long as the slope is fairly uniform. However, a different procedure must be used to estimate $\triangle h$ because the highest and lowest pressures will no longer be at h_l and h_c. This is apparent in figure 7–34 where the pressure is lowest at the manifold position (x/L) = the tangent location (Y).

Use the following steps to compute $\triangle h$ for laterals on slopes steeper than 3 percent.

Step 1 through 3—Follow steps 1 through 3 of the numerical solution above for determining the position for the manifold on sloping fields, except that the equivalent head loss gradient (J′) and the reduction coefficient to compensate for the discharge (F) should be determined for the length of lateral under study rather than for the manifold spacing (S_m).

Step 4—For relatively mild slopes the maximum difference in pressure head ($\triangle h$) along the lateral can be computed by equation 7–72.

$$\triangle h = \frac{L}{100}(J'F + S' - S) \qquad \textbf{(7–72)}$$

Where

J′F = friction gradient found in step 1.
S′ = unusable slope component.
S = average slope of the ground line, percent.

Equation 7–72 is the same as equation 7–71 with x/L = 1 because the manifold would be located at x/L = 1 in figure 7–34.

For steep slopes the maximum difference may occur at the closed end. To test for this possibility, determine the difference between the downstream and minimum pressure heads ($\triangle h_c$) by equation 7–71 or equation 7–71b.

Manifold Design

This section presents the procedures for determining the characteristics of a manifold, flow rate, pipe sizes to keep within the desired pressure-head differential, and inlet pressure needed to give the desired average emitter discharge (q_a).

On fields where the average slope along the manifolds is less than 3 percent, it is usually more economical to install manifolds both uphill and downhill from the main line. The inlet from the main line should be positioned so that starting from a common main line connection the minimum pressures along the pair of manifolds (one to either side of the manifold) are equal. Thus on level ground the pair of manifolds should have equal lengths.

Where the ground slopes along the manifolds (across the rows), the manifold inlet should be shifted uphill from the center. The effect is to shorten the uphill manifold and lengthen the downhill manifold so the combination of friction losses and elevation differences are in balance. This can be done with the aid of a selection graph for tapered manifolds and either graphically or numerically for single-pipe-size manifolds. The numerical procedure is similar to that described for positioning lateral inlets.

The main line layout is a compromise between field geometry and manifold hydraulics. The allowable manifold pressure-head variation may be computed by equation 7–73.

$$(\triangle H_m)_a = \triangle H_s - \triangle h' \qquad \textbf{(7–73)}$$

Where

$\triangle H_s$ = the allowable subunit pressure variation, feet.
$\triangle h'$ = the greater of $\triangle h$ or $\triangle h_c$, the lateral-line pressure variation, feet.

For simplification, the design procedure is based on laterals with the average emitter flow rate (q_a). Thus, for manifolds serving rectangular subunits, the lateral flow rate (q_l) is assumed to be constant.

Characteristics

Manifolds are usually tapered and designed to use pipe of two, three, or four sizes. For adequate flushing, the diameter of the smallest pipe should be no less than one-half that of the largest pipe. The velocity should be limited to about 7 ft/s in manifolds. (This is higher than the 5 ft/s used for main lines because the outlets along the manifold are always open, so water-hammer shock is dampened.)

Length.—When two manifolds extend in opposite directions from a common inlet point, they are referred to as a pair of manifolds. For example, the manifolds serving blocks I and II in figure 7-27 are a pair. If only one manifold is connected at an inlet point, as in figure 7-9, the design is termed a single-manifold configuration.

The length of a pair of manifolds (L_p) can be computed by equation 7-74.

$$L_p = [(n_r)_p - 1]S_r \qquad \textbf{(7-74)}$$

Where

$(n_r)_p$ = number of row (or lateral) spacings served from a common inlet point.
S_r = row spacing, feet.

The length of a single manifold (L_m), feet, is usually equal to that computed by equation 7-75.

$$L_m = (n_r - 1/2)S_r \qquad \textbf{(7-75)}$$

Where

n_r = number of row (or lateral) spacings served by the manifold.
S_r = row spacing, feet.

Inlet position.—For optimal hydraulic design, the inlet to pairs of manifolds should be located so that the minimum pressure in the uphill manifold equals that in the downhill manifold. However, field boundaries, roadways, topographic features such as drains, structures, or existing facilities often dictate the location of main lines and manifold inlets. Furthermore, sometimes the inlet must be positioned to balance system flow rates where manifolds making up pairs are operated individually.

Obviously, for single manifolds the inlet location is fixed. Where a pair of manifolds lies on a contour, the inlet should be in the center of the pair. For pairs of manifolds of a single pipe size serving rectangular subunits, the procedure for locating the inlet is essentially the same as that described for locating lateral-line inlets. To use either the graphical or numerical procedure outlined under Lateral Line Design, replace S_m with L_p and select a suitable pipe size so that the head loss for a manifold with $L_m = L_p/2$ is less than the allowable manifold pressure variation [$(\triangle H_m)_a$], feet.

The inlet location that will balance the minimum uphill and downhill pressures is not precise for tapered manifolds because it depends on the selection of pipe sizes and lengths. Figure 7-35 was developed as a guide to selecting the inlet location for tapered manifolds. The figure's use greatly simplifies the selection process. For example, if the manifold is on the contour, the average slope of the ground line (S), percent, = 0; therefore, the slope ratio is 0 and the distance from the downhill end (x) = 0.5 L_p, which is the center of the pair of manifolds.

Assuming that $(\triangle H_m)_a$ = 0.5 ft for a pair of manifolds with L_p = 1,000 ft and S = 1 percent, the manifold inlet location can be found as follows: slope ratio = 2; x ≅ 0.75 L_p from figure 7-35; therefore, L_m = 750 ft for the downhill manifold and L_m = 250 ft for the uphill manifold.

Proper location of the inlet to pairs of sloping manifolds can increase both uniformity and savings of pipe costs. The pipe cost savings result from replacing the larger diameter pipe at the inlet end of the long downhill manifold with the smaller diameter pipe used for the short uphill manifold.

Inlet pressure.—As a rule, the main pressure-control (adjustment) points are at the manifold inlets. Therefore, the manifold inlet pressure must be known to properly manage the system and determine the total dynamic head required. The manifold

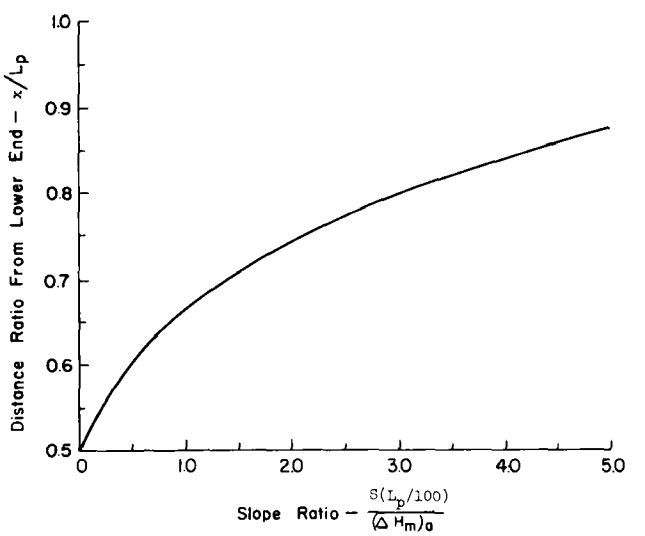


Figure 7-35.—Graph for selecting location of inlet to a pair of tapered manifolds on a slope. x = distance of inlet from closed end; L_p = length of the pair of manifolds; S = average slope of the ground line; $(\triangle H_m)_a$ = allowable manifold pressure variation.

inlet pressure head (H_m), feet, for subunits with single pipe-size laterals can be computed by equations 7–76a and 7–76b.

$$H_m = h_l + \triangle H'_m \qquad \textbf{(7–76a)}$$

Where

h_l = lateral inlet pressure that will give the average pressure head (h_a), feet. For laterals with one tubing diameter on uniform slopes, h_l can be determined either by equation 7–63 or graphically.

$\triangle H'_m$ = difference between the manifold *inlet* pressure and h_l, feet. It can be estimated by:

$$\triangle H'_m = MH_f + 0.5\ \triangle El$$

in which M = 0.75 for manifolds with one pipe size, M = 0.6 for manifolds with two pipe sizes, and M = 0.5 for manifolds with three or more pipe sizes. It can also be estimated graphically.

For tapered laterals:

$$H_m = h_a + \triangle h' + \triangle H'_m \qquad \textbf{(7–76b)}$$

Where

$\triangle h'$ = difference between the lateral inlet pressure and h_a, feet. For tapered laterals $\triangle h'$ should be estimated graphically.

Economic-Chart Design Method

An economic pipe-size selection chart such as figure 7–33 can be used to select pipe sizes and lengths for manifolds serving rectangular subunits. The chart used for a design should be specifically constructed for the pipe materials and wall thicknesses (or pressure ratings) that the design calls for. (Figure 7–33 is designed for PVC thermoplastic IPS pipe with the minimum SDR ratings.) The general procedure for using the economic chart is presented in Pipeline Hydraulics.

The procedure for the economic chart method for designing tapered manifolds is as follows:

Step 1—Compute the annual cost per water horsepower (C_{whp}) by equation 7–57.

Step 2—Determine the system flow-rate adjustment factor (A_f) by equation 7–58.

Step 3—Calculate the adjusted system flow (Q'_s) for entering the chart, gallons per minute, by equation 7–77.

$$Q'_s = A_f q_m \qquad \textbf{(7–77)}$$

Where

q_m = flow rate in the manifold, gallons per minute. (This is equal to the number of laterals served by the manifold times the flow rate per lateral. For a pair of manifolds use the flow rate in the downhill [larger] manifold.)

Step 4—Enter the vertical axis of figure 7–34 with Q'_s, draw a horizontal line across the graph, and record the flow rates (along the bottom axis) where this line intersects the upper limit of each pipe-size region. These are the flow rates at which each subsequently larger pipe diameter should be used. Select no more than four pipe sizes so that the smallest pipe is no less than half the diameter of the largest pipe.

Step 5—Calculate the lengths of each size pipe by equation 7–78.

$$L_d = \frac{q_d - q_{d-1}}{q_m} L_m \qquad \textbf{(7–78)}$$

Where

L_d = length of pipe with diameter d, feet.

q_d = upper-limit flow rate for the pipe with diameter d, gallons per minute.

q_{d-1} = upper-limit flow rate for the pipe with the next smaller diameter, gallons per minute.

L_m = length of the manifold used in computing q_m, feet.

Step 6a—Determine the pressure head loss from pipe friction (H_f) in the tapered manifold. The general theory for doing this is outlined in the Lateral Line Design section. A detailed example of the numerical process is presented under Drip System in Sample Designs for Trickle Irrigation Systems.

Step 6b—Figures 7–36 and 7–37 were prepared to provide a graphical solution that greatly simplifies the calculation of the head loss in a tapered manifold. The figures are plots of the head loss curves for manifolds made up of PVC thermoplastic IPS pipe with different nominal diameters with the minimum SDR ratings. Figure 7–36 is based on manifolds with 2-gpm outlets every 20 ft and figure 7–37 is based on manifolds with 6-gpm outlets every 60 ft. Use figure 7–36 for manifold outlet discharges below 3.4 gpm and figure 7–37 for discharges between 3.4 and 10.2 gpm. (Note that when a manifold feeds pairs of laterals, the outlet discharges are equal to the average discharge to each pair of laterals.)

The H_f values given in figures 7–36 and 7–37 are both based on 0.1 gpm/ft. The H_f values obtained from the figures must be multiplied by a scale factor (k) to reflect the actual manifold discharge per unit length. The dimensionless k can be computed by equations 7–79a and 7–79b.

$$k = (L_m/q_m)(0.1 \text{ gpm/ft}) \qquad \textbf{(7–79a)}$$

$$k = (S_l/q_l)(0.1 \text{ gpm/ft}) \qquad \textbf{(7–79b)}$$

Where

S_l = lateral spacing, feet.
q_l = lateral flow rate, gallons per minute.

To use the graphical method for determining the head loss from pipe friction:

Step 1—Lay a piece of tracing paper on figure 7–36 or 7–37 (depending on q_l) and draw lines through the origin along the abscissa and ordinate.

Step 2—Draw vertical lines at flow rates representing the divisions between successive pipe sizes obtained in step 4.

Step 3—Trace the curve representing the smallest diameter pipe between the origin and the flow rate at which the next largest diameter pipe should begin.

Step 4—Slide the overlay down so that the upper end of this curve (for the smaller pipe) coincides with the curve for the (next) larger pipe at the flow rate where pipe size should change and trace the curve to the next pipe-size change point.

Step 5—Repeat step 4 until the traced set of curve segments reaches q_m.

Step 6—The series of head loss segments represents the head loss in the tapered manifold; and the sum of the head losses in each segment is proportionate to H_f at q_m on the overlay. The actual H_f can be computed by equation 7–80.

$$H_f = k(H_{fg}) \qquad \textbf{(7–80)}$$

Where

H_f = actual pressure-head loss in the manifold from pipe friction, feet.
(H_f) = pressure-head loss in the manifold from pipe friction, taken from graph overlay in above steps, feet.

An example of the graphical solution is presented in figure 7–42 under Manifold Design, Drip System, in Sample Designs for Trickle Irrigation Systems.

Step 7—Estimate manifold pressure-head variation ($\triangle H_m$) for the tapered manifolds by equations 7–81a, 7–81b, and 7–81c. For level manifolds:

$$\triangle H_m = H_f \qquad \textbf{(7–81a)}$$

For uphill manifolds:

$$\triangle H_m = H_f + S(L_m/100) \qquad \textbf{(7–81b)}$$

For downhill manifolds $\triangle H_m$ can be determined graphically, or when $\triangle El < H_f$, it can be approximated by:

$$\triangle H_m = H_f - [S(0.1 - \frac{0.36}{c})\frac{L_m}{100}] \qquad \textbf{(7–81c)}$$

Where

S = slope of the manifold, percent.
c = number of pipe sizes used in the manifold.

Step 8—If $\triangle H_m \leq 1.1$ times the allowable manifold pressure variation $(\triangle H_m)_a$, feet, the design is satisfactory. If $\triangle H_m > 1.1(\triangle H_m)_a$, the manifold pipe sizes must be adjusted to reduce H_f. Small adjustments can usually be made by inspection. For large adjustments calculate a modified system flow rate (Q_s'') by equations 7–82a, 7–82b,

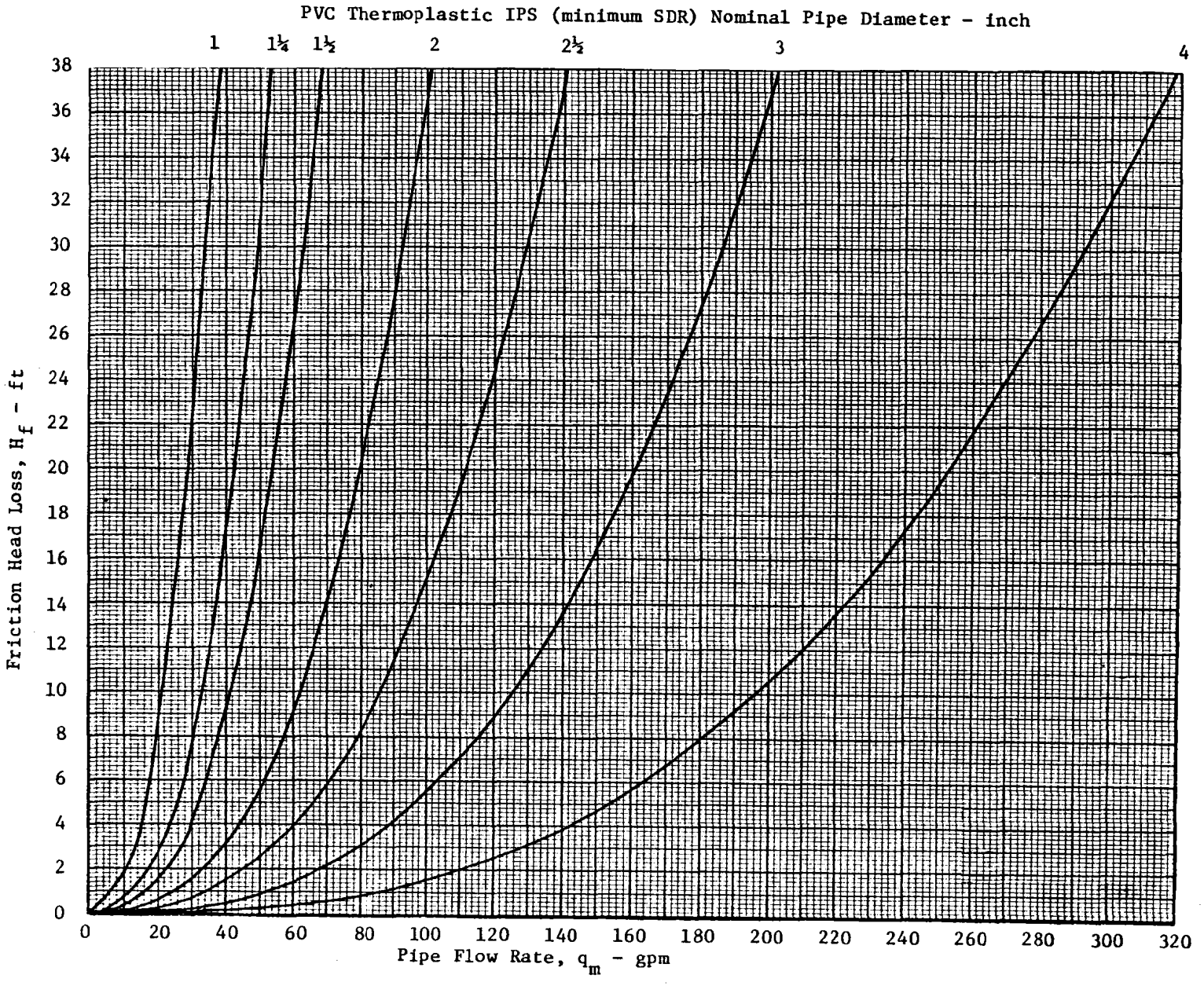


Figure 7-36.—Standard manifold friction curves for 2-gpm outlet every 20 ft.

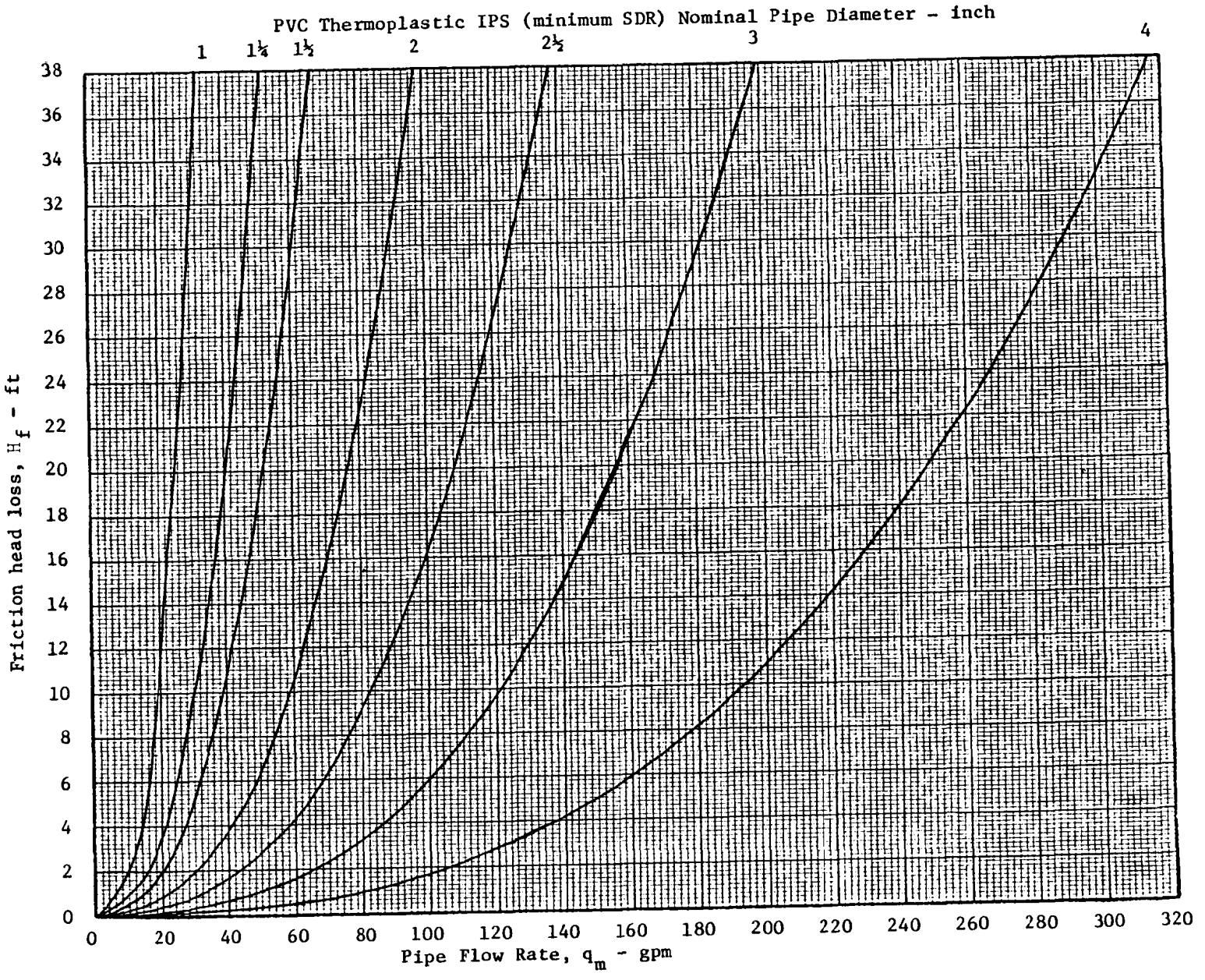


Figure 7-37.—Standard manifold friction curves for 6-gpm outlet every 60 ft.

and 7–82c for reentering the economic pipe-size selection chart. For level manifolds:

$$Q_s'' = \frac{H_f}{(\triangle H_m)_a} Q_s' \qquad \textbf{(7–82a)}$$

For uphill manifolds:

$$Q_s'' = \frac{H_f}{(\triangle H_m)_a - S(L_m/100)} \qquad \textbf{(7–82b)}$$

And for downhill manifolds:

$$Q_s'' = \frac{H_f}{(\triangle H_m)_a + [S(1.0 - \frac{0.36}{c})L_m/100]} \qquad \textbf{(7–82c)}$$

Step 9—Repeat steps 4 through 8, beginning with Q_s'', until $(\triangle H_m)_a$ is satisfactory, as specified in step 8.

Step 10—For pairs of manifolds that operate simultaneously from the same regulating value, compute H_m, using the weighted (by length) uphill and downhill values for the amount $(\triangle H_m')$ the manifold inlet pressure differs from lateral line inlet pressure, by equation 7–77a or 7–77b.

General Graphical-Design Method

The graphical-design procedure for manifolds of a single pipe size is the same as that given under Lateral Line Design. The general graphical-design method that follows can be used for tapered manifolds that serve either rectangular or nonrectangular trapezoidal subunits. It is more time consuming than the economic-chart method (which can be used only for rectangular subunits), but it is more precise. A simpler graphical method can, however, be used on rectangular subunits. The alternate graphical method is designed to use the standard manifold curves (figs. 7–36 and 7–37).

The general graphical-design procedure for tapered manifolds (or laterals) is the same for both rectangular and nonrectangular trapezoidal subunits. However, the reduction coefficient to compensate for the discharge (F) used to compute friction loss in multiple-outlet pipelines and the ratios for plotting the dimensionless pipe-friction loss curves must be adjusted for the subunit shape. The shape factor of the subunit (S_f) is defined by equation 7–83.

$$S_f = \frac{(q_l)_c}{(q_l)_a} = \frac{(n_p)_c}{(n_p)_a} \qquad \textbf{(7–83)}$$

Where

$(q_l)_c$ = flow rate into the lateral (pair) at the closed end of the manifold, gallons per minute.
$(q_l)_a$ = average lateral (pair) flow rate along the manifold, gallons per minute.
$(n_p)_c$ = number of plants in the row at the closed end of the manifold.
$(n_p)_a$ = number of plants in the average row in the subunit.

The pressure head loss from pipe friction in a manifold (H_f), feet, can be computed by equation 7–84.

$$H_f = JFF_s(L_m/100) = JF'(L_m/100) \qquad \textbf{(7–84)}$$

Where

J = head loss gradient of a pipe, feet per 100 feet.
F_s = manifold pipe-friction adjustment factor, figure 7–37.
JF′ = scalar ratio for field shape.
L_m = actual length of the manifold, feet.

The general graphical method for designing tapered manifolds is as follows:

Step 1—Determine the largest pipe size to be used in the manifold. This will be the smallest pipe that will give a manifold pressure-head variation ($\triangle H_m$) < the allowable manifold pressure variation [$(\triangle H_m)_a$] by equation 7–81 or possibly one pipe size larger.

To do this:

1. First compute S_f by equation 7–83.
2. Then find F_s for S_f in figure 7–38.
3. Find the value of J in Appendix B.
4. Find F in table 7–6.
5. Compute H_f by equation 7–84.
6. Use H_f in equation 7–81a, 7–81b, or 7–81c to find $\triangle H_m$.

Step 2—Determine four scalar ratios for field shape (JF′) values for manifold flow rate (q_m), gallons per minute, using the largest and three next smaller pipe sizes. (The diameter of the mani-

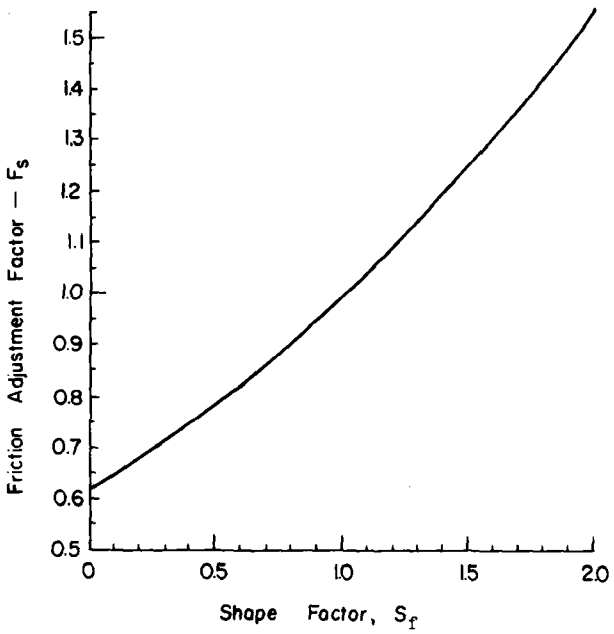


Figure 7-38.—Graph for determining manifold pipe-friction adjustment factors for trapezoidal subunits.

fold's smallest pipe should be at least half the diameter of the manifold's largest pipe.)

If the range of flow rates given by the appropriate table in Appendix B does not include the required q_m, select from the table the value of the head loss gradient of the manifold pipe (J), feet per 100 feet, as J_x for the largest flow rate (q_x) given for the required pipe size. The required J value can then be computed by equation 7-85.

$$J = J_x\left(\frac{q_m}{q_x}\right)^{1.8} \qquad \textbf{(7-85)}$$

Where

J_x = J value from Appendix B for the largest flow rate in the table for the required pipe size, feet per 100 feet.

q_x = largest flow rate (Q) in the appropriate table for pipe size in Appendix B, gallons per minute.

Step 3—Set up a table to organize the dimensionless data for plotting a set of curves scaled to represent each of the four sizes of pipe. (See table 7-9.) First select the proper values for JF′

Table 7-9.—Scaled values of $\triangle H_m/(L/100)$ for constructing a set of dimensionless manifold friction-loss curves for manifold flow rate (q_m) = 178 gpm and reduction coefficient to compensate for discharge (F) = 0.38

		$\triangle H_m/(L/100)$ at indicated pipe size (in.) and JF′)			
	JF′[2]	2	2½	3	4
x/L[1]	ratio	11.09	4.41	1.59	0.42
0.10	0.002	0.02	0.01	0.003	0
0.20	0.013	0.14	0.06	0.02	0.005
0.25	0.023	0.26	0.10	0.04	0.01
0.30	0.037	0.41	0.16	0.06	0.02
0.35	0.057	0.63	0.25	0.09	0.02
0.40	0.081	0.90	0.36	0.13	0.03
0.45	0.112	1.24	0.49	0.18	0.05
0.50	0.149	Velocity	0.66	0.24	0.06
0.55	0.193	limit	0.85	0.31	0.08
0.60	0.245		1.08	0.39	0.10
0.65	0.305		1.35	0.48	0.13
0.70	0.374		Velocity	0.59	0.16
0.75	0.452		limit	0.72	0.19
0.80	0.540			0.86	0.23
0.85	0.638			1.01	0.27
0.90	0.747			1.19	0.31
0.95	0.868			1.38	0.36
1.00	1.000			1.59	0.42

[1]It is normally sufficient to use only the 0.1, 0.2, 0.3, . . . 1.0 values of x/L.
[2]Note that scalar ratios (JF′) from table 7-10 were divided by 10.

ratio vs. x/L for the nearest S_f from table 7–10.

Then multiply the JF′ values found in step 2 for each of the four pipe sizes by each of the JF′ ratios from the table. There is, however, no need to compute values representing velocities greater than 7 ft/s. Furthermore, the full 0.1, 0.2. . . values should give enough data points.

Step 4—Plot the data tabulated in step 3 on regular graph paper with (x/L) as the abscissa and $\triangle H_m/(L/100)$ as the ordinate (see figure 7–39). This set of curves represents a set of four single-size pipe manifolds drawn to a single dimensionless scale.

Step 5—Determine the dimensionless allowable head-loss ratio (j) by equation 7–86.

$$j = \frac{(\triangle H_m)_a}{L_m/100} \qquad \textbf{(7–86)}$$

This represents the allowable pipe-friction loss following the same proportional scale as the set of pipe friction curves.

Step 6—Place a transparent overlay on the set of dimensionless pipe-friction curves, then trace the horizontal and vertical scales and the left vertical boundary (see figure 7–40).

Step 7a—For level manifolds draw a sloping line through the origin and through j at x/L = 1. Then draw a second sloping line parallel to the first and passing through 0.9j at x/L = 1. (See the solid and dashed lines in figure 7–40.)

Step 7b—For steeply (down) sloping manifolds (or pairs of manifolds) where S > 3j, draw a sloping line from the origin to $S = \triangle El/100L$ at x/L = 1. (This line represents the ground slope drawn to the same scale as the friction curves.) Then draw a second line above and parallel to the ground slope line and passing through (j + S) at x/L = 1. (See the solid and dashed lines in figure 7–41).

Step 7c—For mildly (down) sloping manifolds (or pairs of manifolds) where S < 3j, draw a sloping line from 0.15S at x/L = 0 to (j + S) at x/L = 1. Then draw a second line below and parallel to the first and passing through 0.9(j + S) at x/L = 1.

Table 7–10.—Scalar JF′ ratios for constructing dimensionless curves of x/L vs. $\triangle H_m/(L/100)$ for various field-shape factors (S_f)[1]

	JF′ ratio for indicated S_f				
x/L	0.0	0.5	S_f = 1.0	1.5	2.0
0.10	0.00	0.01	0.02	0.03	0.05
0.20	0.01	0.06	0.13	0.19	0.25
0.25	0.02	0.11	0.23	0.34	0.44
0.30	0.04	0.20	0.37	0.54	0.69
0.35	0.08	0.31	0.57	0.80	1.00
0.40	0.15	0.47	0.81	1.12	1.38
0.45	0.26	0.68	1.12	1.50	1.83
0.50	0.42	0.96	1.49	1.95	2.34
0.55	0.64	1.30	1.93	2.47	2.91
0.60	0.96	1.73	2.45	3.05	3.55
0.65	1.38	2.26	3.05	3.70	4.23
0.70	1.94	2.90	3.74	4.42	4.97
0.75	2.66	3.66	4.52	5.20	5.74
0.80	3.58	4.57	5.40	6.05	6.56
0.85	4.73	5.46	6.38	6.95	7.39
0.90	6.16	6.89	7.47	7.92	8.25
0.95	7.90	8.33	8.68	8.93	9.12
1.00	10.00	10.00	10.00	10.00	10.00

[1] In all cases, flow is from left to right.

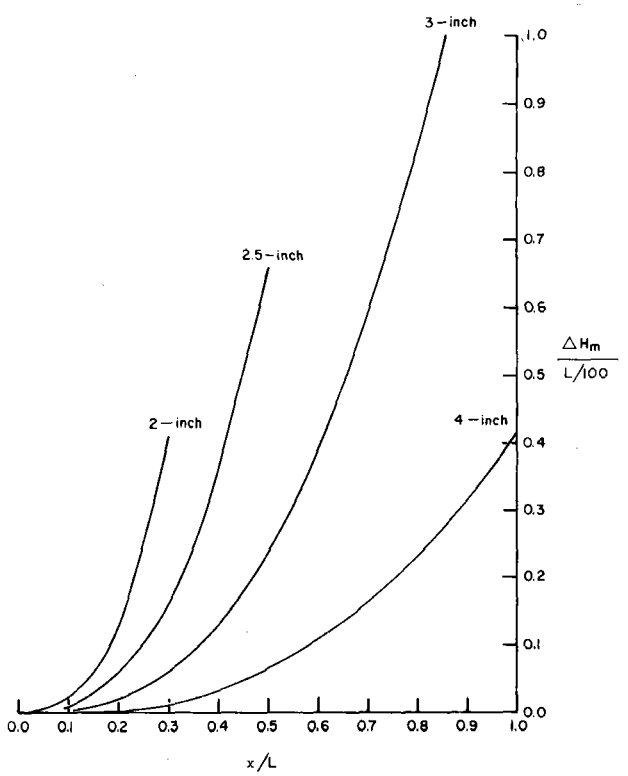


Figure 7–39.—Dimensionless manifold friction curves scaled to represent manifold flow rate (q_m) = 178 gpm through each size of pipe. x = position of point on manifold; L = length of manifold; $\triangle H_m$ = manifold pressure-head variation.

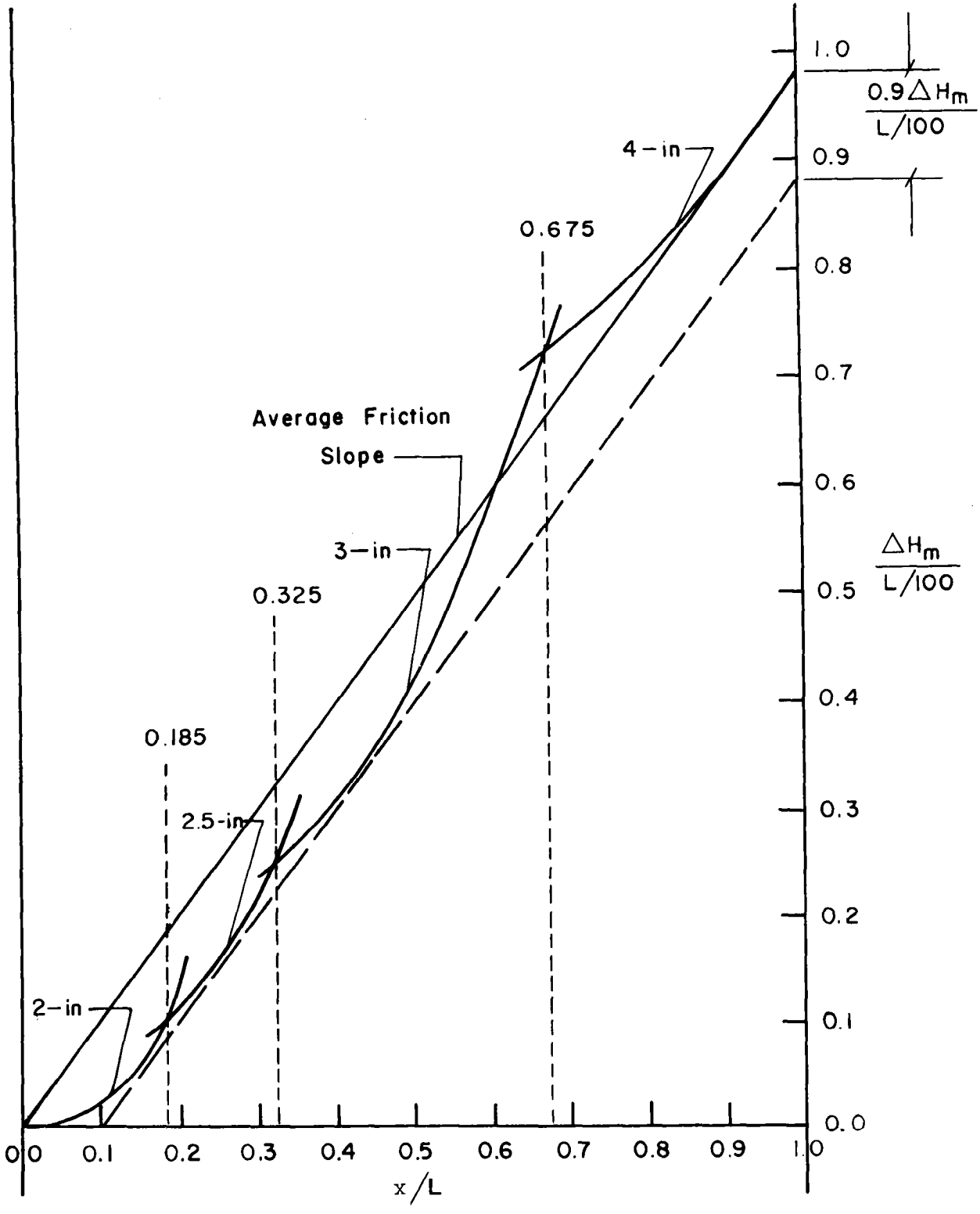


Figure 7-40.—Overlay for design of manifolds (1), (2), and (3) using the general graphical-design method. X = position of point on manifold; L = length of manifold; ΔH_m = manifold pressure-head variation.

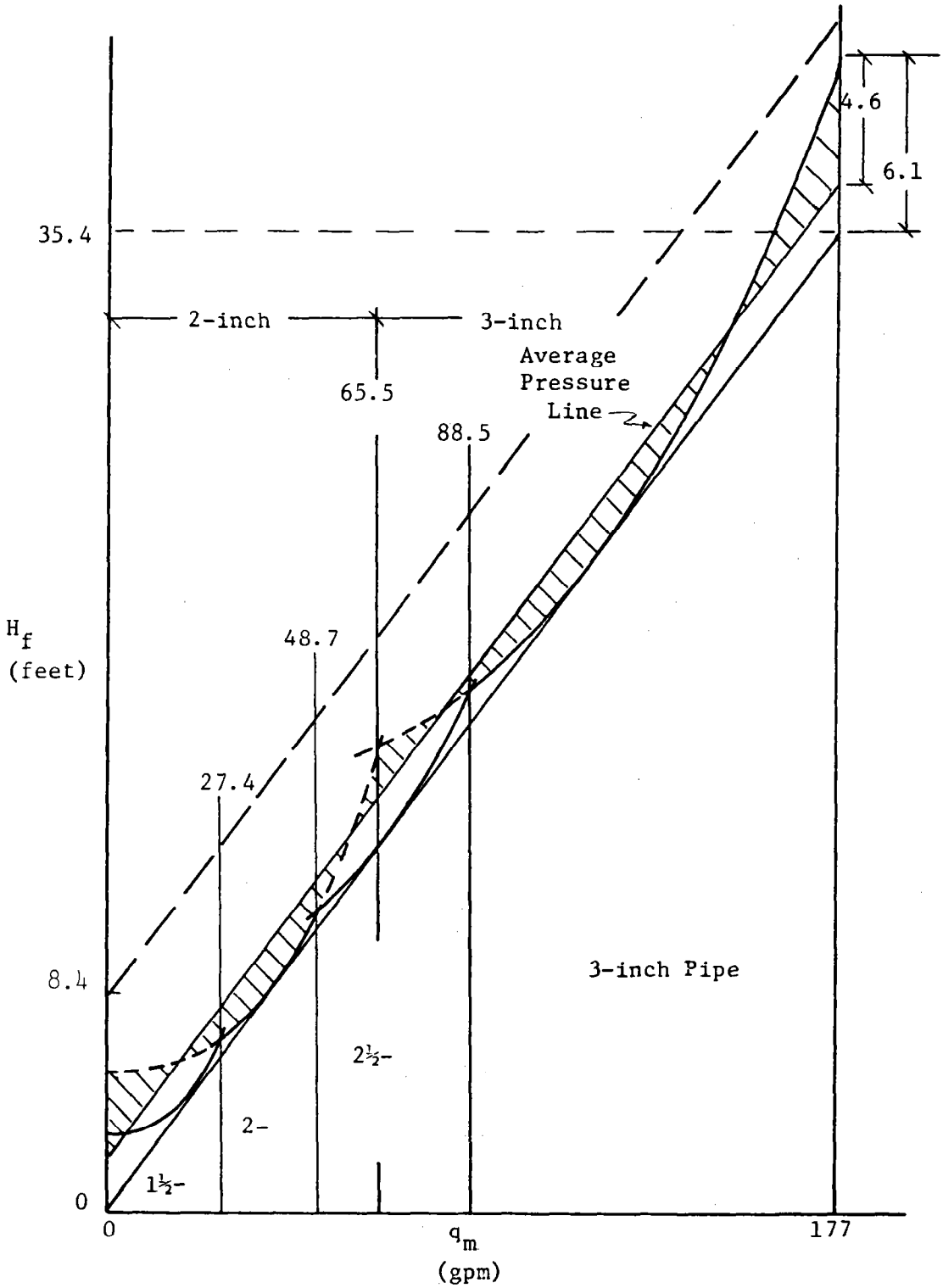


Figure 7–41.—Friction curve overlay to demonstrate graphical method using a standard manifold curve for designing a tapered manifold for a steep slope. H_f = manifold pressure-head loss from pipe friction; q_m = manifold flow rate.

Step 7d—For manifolds running up slope, draw a sloping line for S at x/L = 0 to 0 at x/L = 1. Then draw a horizontal line from j at x/L = 0 to x/L = 1.

Step 8—The most economical design of each manifold is defined by the pairs of lines developed in step 7. The final design is represented by a combination of dimensionless pipe-curve sections representing various pipe diameters and lengths. The procedure for drawing the composite curve is as follows:

1. Start at the origin and trace the friction curve of the smallest permissible pipe from the origin to its intersection with the average friction-slope line.
2. Slide the overlay down until the friction curve of the second pipe size is tangent to the lower limit line. Trace the friction curve from its intersection with the previous friction curve to its intersection with the average friction-slope line.
3. Slide the overlay down, repeating step 2. This time, however, it will be necessary to extend the friction curve well beyond the average friction-slope line.
4. Slide the overlay down until the intersection of the average friction-slope line coincides with the x/L = 1 intercept of the friction curve of the largest pipe to be used. Now trace the friction curve until it intersects with the previous curve segment.

Alternative Graphical-Design Method

The alternative graphical-design method is similar to the general method except that, for rectangular subunits, the set of standard manifold curves presented in figures 7–36 and 7–37 can be used. This eliminates the need for computing and drawing a special set of curves for each set of design conditions. Steps 2, 3, and 4 in the general procedure can be eliminated, and step 1 can be more easily handled by trial and error.

After selection of the proper set of standard manifold curves (see step 6b under Economic-Chart Design Method), the procedure is similar to steps 5 through 8 of the general graphical-design method. Therefore, begin with step 5′ so the comparison can be better visualized.

Step 5′—The standard manifold curves give the manifold pressure-head loss (H_f) for a 0.1-gpm/ft average manifold discharge. Therefore, the allowable manifold-pressure variation [$(\triangle H_m)_a$], feet, and slope along the manifold (S) must be properly scaled to compensate for the difference between the standard curves and the manifold under study. This can be done by equations 7–87 and 7–88.

$$j' = \frac{(\triangle H_m)_a}{k} \qquad \textbf{(7–87)}$$

Where

j' = $(\triangle H_m)_a$ value properly scaled for the manifold under study, feet.
k = scale factor computed by equation 7–80a or 7–80b.

$$S' = \frac{SL_m}{100k} = \frac{Sq_m}{10} = \frac{\triangle El}{k} \qquad \textbf{(7–88)}$$

Where

S' = elevation (from S) properly scaled for the manifold under study, feet.
L_m = actual length of the manifold, feet.
q_m = actual flow rate in the manifold, gallons per minute.
$\triangle El$ = difference in elevation along the manifold, feet.

Step 6′—Place a transparent overlay on the set of standard manifold curves, then trace the horizontal and vertical scales and draw a vertical line at q_m (see figure 7–42).

Step 7′—For level manifolds draw a sloping line through the origin and j′ at q_m. Then draw a sloping line parallel to it and passing through 0.9 j′ at q_m. (See the solid and dashed lines on figure 7–42.)

Step 7b′—For steeply (down) sloping manifolds (or pairs of manifolds) where $S' > 3j'$, draw a sloping line from the origin to S′ at q_m. (This line represents the ground slope drawn to the same scale as the friction curves.) Then draw a second line above and parallel to the ground slope line and passing through (j′ + S′) at q_m. (See the solid and dashed lines in figure 7–41.)

Step 7c′—For mildly (down) sloping manifolds (or pairs of manifolds) where $S' < 3j'$, draw a sloping line from 0.15S′ at $q_m = 0$ to (j′ + S′) at q_m. Then draw a second line below and parallel to it

passing through $0.9(j'+S')$ at q_m.

Step 7d'—For manifolds running up slope draw a sloping line from S' at $q_m = 0$ to 0 at q_m. Then draw a horizontal line from j' at $q_m = 0$ to q_m.

Step 8'—This is the same as step 8 for the general graphical-design method.

Estimating Pressure Loss From Pipe Friction

The pressure head loss from pipe friction (H_f) can be estimated from the H_f of a similar manifold (or lateral) by equation 7–89.

$$(H_f)_2 = \frac{L_2}{L_1} \frac{(F_s)_2}{(F_s)_1} \left(\frac{q_2}{q_1}\right)^{1.8} (H_f)_1 \qquad \textbf{(7–89)}$$

Where

$(H_f)_2$ = estimate of the pressure head loss from pipe friction for the manifold, feet.

$(H_f)_1$ = pressure head loss from pipe friction for the original manifold, feet.

L_1 = length of pipe in the original manifold, feet.

L_2 = length of pipe in the manifold for which $(H_f)_2$ is being estimated, feet.

$(F_s)_1$ = friction adjustment factor for the original manifold.

$(F_s)_2$ = friction adjustment factor for the manifold for which $(H_f)_2$ is being estimated.

q_1 = flow rate in the original manifold, gallons per minute.

q_2 = flow rate in the manifold for which $(H_f)_2$ is being estimated, gallons per minute.

The estimated $(H_f)_2$ will be quite accurate as long as the proportional lengths of the various sizes of pipe in tapered manifolds remain constant and the difference between $(F_s)_1$ and $(F_s)_2$ is less than 0.25. If the lengths and subunit shapes are the same, the discharges can vary over a wide range without reducing the accuracy of the $(H_f)_2$ estimate.

Locating the H_m Line and Estimating $\triangle H'_m$

A graphical technique for estimating the manifold head loss can also be used to estimate $\triangle H'_m$ (the amount the manifold inlet pressure [H_m] differs from the lateral-line inlet pressure [h_l]). The $\triangle HH'_m$ is represented by the distance H_m and a line representing the average manifold pressure (H_a) that lies parallel to the slope. The H_a line is positioned so that the areas between it and the friction curve are the same above and below. To aid in locating the H_a line, place the transparent overlay on a piece of graph paper with one heavy grid line. Adjust the overlay and count squares until the above conditions are satisfied as shown in figure 7–41.

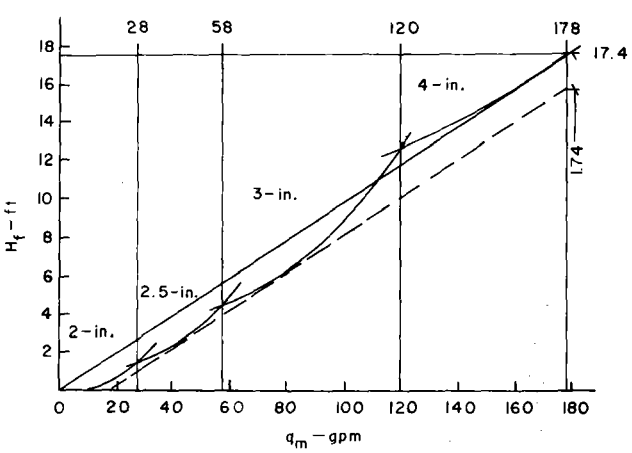


Figure 7–42.—Friction curve overlay demonstrating the graphical solution for using standard manifold curves to design tapered manifolds with a given allowable manifold pressure variation $(\triangle H_m)_a$. H_f = manifold pressure-head loss; q_m = actual flow rate in the manifold.

Sample Designs for Trickle Irrigation Systems

The following sample designs illustrate the procedures of this handbook.

Drip System

The following drip-system design is for a typical deciduous orchard. The data that should be collected before beginning a design are summarized in the trickle-irrigation-design data sheet (fig. 7–43) and the orchard layout map (fig. 7–44).

In addition to illustrating the general process for designing a drip irrigation system, the example emphasizes the following procedures:

1. Selecting the emitter or emission point spacing (S_e), the lateral spacing (S_l), the duration of application (T_a), the number of stations (N), and the average emitter discharge (q_a) and operating pressure head (h_a).
2. Determining $\triangle H_s$, the allowable variation in pressure head that will produce the desired uniformity of emission.
3. Positioning the manifolds and designing the laterals (with both graphical and numerical solutions) for sloping rows.
4. Designing the manifold and selecting economical pipe sizes for both manifolds and main lines.
5. Computing system capacity and total dynamic operating-head requirements.

Design Factors

Before designing the hydraulic network, the designer must determine the emitter spacing (S_e), average emitter discharge (q_a), average emitter pressure head (h_a), allowable head variation ($\triangle H_s$), and hours of operation per season (Q_t).

The steps for developing these factors are outlined in the trickle-irrigation design factors sheet (fig. 7–45). This data sheet serves as a guide and provides a convenient place to record results of the various trial and final computations.

Field observations of trickle irrigation systems in the same area have shown that the wetted diameter produced by 1.0-gph emitters is between 8 and 9 ft. For a continuous wetted strip, the spacing between emitters in the row should not exceed 80 percent of the wetted diameter. Therefore, for the 24-ft tree spacing, a uniform S_e of 6.0 ft was selected. (Table 7–2 can help predict the areas wetted by an emitter; however, field test data and observations at existing systems are preferable.)

Percent area wetted (P_w).—S_e = 6.0 ft, S_w = 8.5 ft (field data), S_p = 24 ft, S_r = 24 ft, e′ = 4.0

$$P_w = \frac{4.0 \times 6 \times 8.5 \times 100}{24 \times 24} \qquad (7\text{–}1)$$

$$P_w = 35.42\%$$

Maximum net depth of application (F_{mn}).—M_{ad} = 30%, WHC = 1.8 in./ft, RZD = 6.0 ft, P_w = 35.42%.

$$F_{mn} = 0.30 \times 1.8 \times 6.0 \times 0.3542 \qquad (7\text{–}4)$$

$$F_{mn} = 1.15 \text{ in}$$

Average peak daily transpiration rate (T_d) and seasonal transpiration rate (T_s).—From *Irrigation Water Requirements*:[5] U = 36.74 in., u_m = 8.83 in. for July, u_d = 8.83/31 = 0.28 in., P_s = 78% (field data).

i) $T_d = 0.28[0.78 + 0.15(1.0 - 0.78)]$ (7–5)

$T_d = 0.23$ in./day

ii) $T_s = U[P_s + 0.15(0.1 - P_s)]$

$= 36.74[0.78 + 0.15(1.0 - 0.78)]$

$T_s = 29.87$ in./yr

Maximum allowable irrigation interval (days) (I_f).—F_n = 1.15 in., T_d = 0.23 in./day.

$$1.15 = 0.23 I_f \qquad (7\text{–}6)$$

$$I_f = 1.15/0.23$$

$$I_f = 5.0 \text{ days}$$

Design irrigation interval (days) (I_f).—I_f = 1 day will be used in developing the design factors, because the actual interval used is a management decision and does not affect the design hydraulics.

Net depth of application (F_n).—T_d = 0.23 in./day, I_f = 1.0 day, assume daily irrigations.

$$F_n = 0.23 \times 1.0 \qquad (7\text{–}6)$$

$$F_n = 0.23 \text{ in.}$$

Emission uniformity (EU).—An emission uniformity of 90 percent is a practical design objective for drip systems on relatively uniform topography.

[5]Soil Conservation Service. 1967. Irrigation Water Requirements. U.S. Dep. Agric. Soil Cons. Serv. Tech. Release 21.

I	Project Name--Happy Green Farm	Date-Winter 1978
II	Land and Water Resources	
	a) Field no.	#1
	b) Field area (acres), A	115.68
	c) Average annual effective rainfall (in.), R_e	3.7
	d) Residual stored soil moisture from off-season precipitation (in.), W_s	0
	e) Water supply (gpm)	800
	f) Water storage (acre-ft)	--
	g) Water quality (mmhos/cm), EC_w	1.4
	h) Water quality classification	Good
III	Soil and Crop	
	a) Soil texture	Silt loam
	b) Available water-holding capacity (in./ft), WHC	1.8
	c) Soil depth (ft)	10
	d) Soil limitations	None
	e) Management-allowed deficiency (%), M_{ad}	30
	f) Crop	Almonds
	g) Plant spacing (ft x ft), $S_p \times S_r$	24 x 24
	h) Plant root depth (ft), RZD	6
	i) Percent area shaded (%), P_s	78
	j) Average daily consumptive-use rate for the month of greatest overall water use (in./day), u_d	0.28
	k) Season total crop consumptive-use rate (in.), U	36.74
	l) Leaching requirement (ratio), LR	0
IV	Emitter	
	a) Type	Vortex
	b) Outlets per emitter	1
	c) Pressure head (psi), h	15.0
	d) Rated discharge @ h (gph), q	1.0
	e) Discharge exponent, x	0.42
	f) Coefficient of variability, v	0.07
	g) Discharge coefficient, k_d	0.32
	h) Connection loss equivalent (ft), f_e	0.4

Figure 7–43.—Drip-system data for a deciduous orchard in the Central Valley of California.

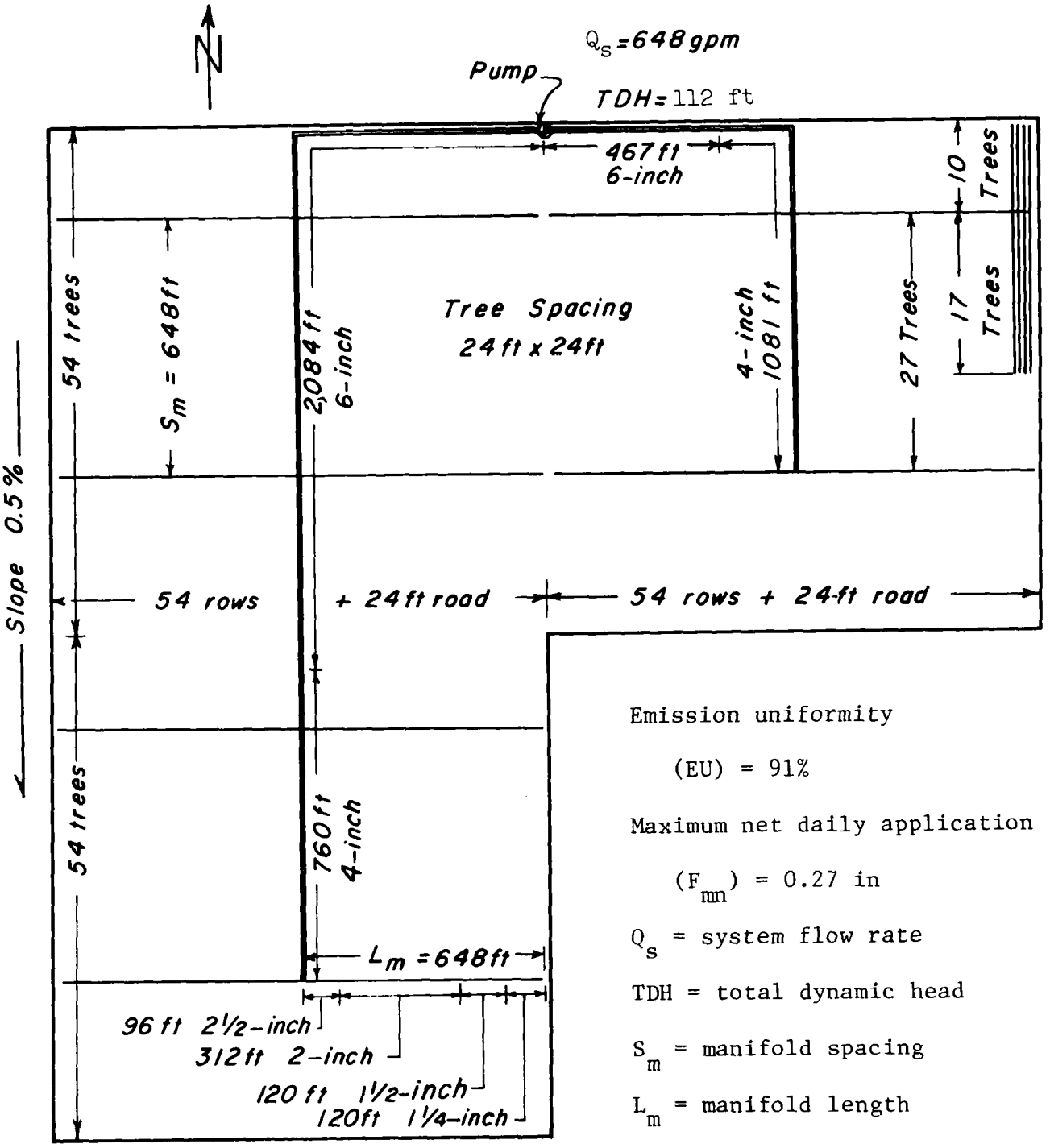


Figure 7-44.—Orchard layout with sample design for a drip irrigation system. (Lateral lines are 0.58-in. polyethylene (PE), manifolds are SDR 26 polyvinyl chloride (PVC), and main lines are SDR 41 PVC.)

I	Project Happy Green Farm	Date-Winter 1978
II	Trial Design	
	a) Emission point layout	St. line
	b) Emitter spacing (ft x ft), S_e x S_l	6 x 24
	c) Emission points per plant, e'	4
	d) Percent area wetted (%), P_w	35.42
	e) Maximum net depth of application (in.), F_{mn}	1.15
	f) Ave. peak-of-application daily transpiration rate (in./day), T_d	0.23
	g) Maximum allowable irrigation interval (days), I_f	5.0
	h) Design irrigation interval (days), I_f	1.0
	i) Net depth of application (in.), F_g	0.23
	j) Emission uniformity (%), EU	90
	k) Gross water application (in.), F_g	0.26
	l) Gross volume of water required per plant per day (gal/day), $F_{(gp/d)}$	93.30
	m) Time of application (hr/day), T_a	23.33
III	Final design	
	a) Time of application (hr/day), T_a	21.0
	b) Design irrigation interval (days), I_f	1.0
	c) Gross water application (in.), F_g	0.26
	d) Average emitter discharge (gph), q_a	1.11
	e) Average emitter pressure head (ft), h_a	44.65
	f) Allowable pressure-head variation (ft), ΔH_s	16.05
	g) Emitter spacing (ft x ft), S_e x S_l	6 x 24
	h) Percent area wetted (%), P_w	35
	i) Number of stations, N	1
	j) Total system capacity (gpm), Q_s	647.37
	k) Seasonal irrigation efficiency (%), E_s	90
	l) Gross seasonal volume (acre/ft), V_i	319.94
	m) Seasonal operating time (hr), Q_t	2,686
	n) Total dynamic head (ft), TDH	112
	o) Emission uniformity (%), EU	91

Figure 7–45.—Drip-system design factors for a deciduous orchard in the Central Valley of California.

Average peak daily transpiration ratio (T_r).—Because the crop is deep rooted and the soil is medium texture, $T_r = 1.00$ as discussed in Gross Water Application under Soil-Plant-Water Considerations.

Leaching requirement ratio (LR_t).—Obtain $EC_w = 1.4$ mmhos/cm from figure 7–43. Obtain min $EC_e = 1.5$ mmhos/cm and max $EC_e = 7$ mmhos/cm from table 7–4 for almonds.

$$\text{i)}\quad LR_t = \frac{1.4}{2(7)} = 0.10 \qquad \textbf{(7–17)}$$

ii) Proper leaching should not reduce yield, because $EC_w <$ min EC_e (see equation 7–15).

Gross water application (F_g).—$T_r = 1.00$, $LR_t = 0.1$, $F_n = 0.23$ in./hr, EU = 90%.

i) When the unavoidable losses are greater than the leaching requirement, i.e., $T_r \geq 1/(1.0 - LR_t)$, or

ii) When $LR_t \leq 0.1$, then extra water for leaching is not required during the peak use period and F_g should be computed by equation 7–8a.

$$\text{iii)}\quad F_g = \frac{0.23 \times 1.00}{0.90} \qquad \textbf{(7–8a)}$$

$$F_g = 0.26 \text{ in.}$$

Gross volume of water required per plant per day [$F_{(gp/d)}$].—$F_g = 0.26$ in., $S_p = 24$ ft, $S_r = 24$ ft, $I_f = 1$ day.

$$F_{(gp/d)} = \frac{0.623 \times 0.26 \times 24 \times 24}{1} \qquad \textbf{(7–9)}$$

$$F_{(gp/d)} = 93.30 \text{ gal/day}$$

Time of application (T_a).—$F_{(gp/d)} = 93.30$ gal/day, $e = 4$, $q_a = 1.0$ gph.

$$\text{i)}\quad T_a = \frac{93.3}{4 \times 1.0} \qquad \textbf{(7–30)}$$

$$T_a = 23.33 \text{ hr/day} > 21.6$$

ii) Adjusting q_a would bring T_a to within the allowable limits, i.e., 90 percent of 24 = 21.6 hr/day. Because $T_a \cong 23$ hr, one station will be used for the system and the q_a will be increased to give 93.3 gal/day in 21.6 hr or less. (If $T_a \cong 12$ hr, two stations can be used, and if $T_a \cong 6$ hr, four stations can be used.)

iii) For added safety and convenience of operation let $T_a = 21.0$ hr.

Average emitter discharge (q_a).—$T_a = 21.0$ hr, $F_{(gp/d)} = 93.3$ gal/day, $e' = 4.0$.

The q_a that will apply the desired volume of water in $T_a = 21.0$ hr is

$$21.0 = \frac{93.3}{4.0\, q_a} \qquad \textbf{(7–30)}$$

$$q_a = \frac{93.3}{4.0 \times 21.0}$$

$$q_a = 1.11 \text{ gph.}$$

Average emitter pressure head (h_a).—$q = 1.0$ gph, $h = 15.0$ psi, $x = 0.42$, $q_a = 1.11$ gph.

i) Compute emitter discharge coefficient (k_d) from the standard emitter flow-rate data given.

$$1.0 = k_d(15.0)^{0.42} \qquad \textbf{(7–20)}$$

$$k_d = 1.0/(15.0)^{0.42}$$

$$k_d = 0.32 \text{ gph/(psi)}^{0.42}$$

ii) The adjusted value of h_a that will give q_a is

$$h_a = \left(\frac{1.11}{0.32}\right)^{1/0.42} \qquad \textbf{(7–31)}$$

$$h_a = 19.33 \text{ psi or } 44.65 \text{ ft.}$$

Allowable pressure-head variation ($\triangle H_s$)—(subunit).—$e' = 4$, $v = 0.07$, $q_a = 1.11$ gph, EU = 90%, $k_d = 0.32$, $x = 0.42$, $h_a = 19.33$ psi.

i) A subunit is that part of the system beyond the last pressure-regulation point; i.e., if a valve is used to adjust the inlet pressure to a manifold that has no other pressure regulator, the area served by the manifold is a subunit. The object is to limit the pressure variation within a subunit so that actual emission uniformity (EU) will equal or exceed the assumed value of EU.

ii) Rearranging equation 7–33a, the minimum permissible flow, q_n, is

$$q_n = \frac{1.11 \times 90/100}{1.0 - (0.07 \times 1.27/\sqrt{4})}$$

$$q_n = 1.05 \text{ gph.}$$

iii) The minimum permissible pressure head (h_n) that would give q_n is

$$h_a = \left(\frac{q_a}{k_d}\right)^{1/x} \qquad \textbf{(7–31)}$$

$$q_n = q_a\left(\frac{h_n}{h_a}\right)^x \qquad \textbf{(7–38)}$$

$$\left(\frac{q_n}{q_a}\right) = \left(\frac{h_n}{h_a}\right)^x = > h_n = h_a\left(\frac{q_n}{q_a}\right)^{1/x}$$

$$h_n = \left(\frac{q_a}{k_d}\right)^{1/x}\left(\frac{q_n}{q_a}\right)^{1/x}$$
$$= \left(\frac{q_n}{k_d}\right)^{1/x}$$
$$= (1.05/0.32)^{1/0.42}$$
$$h_n = 16.93 \text{ psi.}$$

iv) Therefore, the allowable variation in pressure head for the subunit, $\triangle H_s$, is

$$\triangle H_s = 2.5(19.33 - 16.93) \quad \textbf{(7–34)}$$
$$\triangle H_s = 6.0 \text{ psi or } 13.86 \text{ ft.}$$

Total system capacity (Q_s).—A = 115.7 acres, q_a = 1.11 gph, n = 1.0, S_e = 6 ft, S_l = 24 ft.

$$Q_s = \frac{726 \times 115.7 \times 1.11}{1.0 \times 6 \times 24} \quad \textbf{(7–35b)}$$
$$Q_s = 648 \text{ gpm}$$

Seasonal irrigation efficiency (E_s).—EU = 90%, obtain T_R = 1.00 from table 7–3, LR_t = 0.10.

i) The seasonal irrigation efficiency is the product of EU/100, the expected efficiency of irrigation scheduling, and the inverse of the proportions of the applied water that may be lost to runoff, leaching, or evaporation, or any combination of the three.

ii) Because a commercial scheduling service will be employed for this operation and little runoff, leakage, or evaporation is anticipated:

$$T_R < 1/(1.0 - LR_t).$$

iii) Considering the above, the seasonal irrigation efficiency (E_s) will be

$$E_s = 90\%. \quad \textbf{(7–11)}$$

Gross seasonal volume (V_i).—U = 36.74 in., R_e = 3.7 in., W_s = 0, P_s = 78%, E_s = 90%, A = 115.68 acres, LR_t = 0.1

i) The annual net depth of application [$F_{(an)}$] is

$$F_{(an)} = 33.04[0.78 + 0.15(1.0 - 0.78)] \quad \textbf{(7–10)}$$
$$F_{(an)} = 26.9 \text{ in.}$$

ii) The gross seasonal volume of irrigation water required (V_i) is

$$V_i = \frac{26.9 \times 115.7}{12(1 - 0.1)90/100} \quad \textbf{(7–14)}$$
$$V_i = 320 \text{ acre-ft.}$$

Seasonal operating time (Q_t).—V_i = 320 acre-ft, Q_s = 648 gpm.

$$Q_t = \frac{5{,}430 \times 320}{648} \quad \textbf{(7–37)}$$
$$Q_t = 2{,}682 \text{ hr}$$

Lateral Line Design and System Layout

The procedure for designing a lateral line involves determining the manifold spacing and lateral characteristics, manifold position, lateral inlet pressure, and pressure difference along the laterals.

The procedure for selecting the manifold spacing is presented under Lateral Line Design. It is convenient to have the same spacing throughout the field.

Manifold spacing (S_m).—S_p = 24 ft, S_e = 6 ft, q_a = 1.11 gph, ID = 0.58 in.; from Appendix B, J = 5.73 ft/100 ft; f_e = 0.4 ft; from table 7–6, F = 0.36; $\triangle H_s$ = 16.05 ft, S_p = 24 ft.

i) Inspection of the orchard layout shows that three manifolds, each serving rows of 54 trees, would be the fewest to meet the criteria, i.e., two manifolds for the west 80 acres and one manifold for the east 40 acres.

ii) The difference in pressure head ($\triangle$h) for the level laterals serving 27 trees on either side of each manifold can be calculated as follows:

$$l = 27 \times 24$$
$$l = 648 \text{ ft,}$$

and

$$q_l = \frac{648}{6} \times \frac{1.11}{60} \quad \textbf{(7–62)}$$
$$q_l = 2.00 \text{ gpm.}$$

Taking into account the added roughness from the emitter connections to the laterals,

$$J' = 5.73\left(\frac{6.0 + 0.4}{6.0}\right) \quad \textbf{(7–51b)}$$
$$J' = 6.11 \text{ ft/100 ft.}$$

Therefore,

$$\triangle h = h_f = 6.11 \times 0.36 \times 6.48 \qquad (7\text{–}52)$$
$$\triangle h = 14.26 \text{ ft.}$$

iii) This $\triangle h$ is considerably greater than 0.5 $\triangle H_s$ and would leave too little margin for differences in pressure head in the manifold.

The lateral length that would produce $h = 0.5\triangle H_s$ and $\triangle H_s = 8.03$ ft can be found directly by using the 14.26-ft head loss computed for the 648-ft-long lateral by equation 7–65b.

$$l = 648\left(\frac{8.03}{14.26}\right)^{1/2.75}$$
$$l = 526 \text{ ft (about 22 trees)}$$

This would give a manifold spacing of

$$S_m = 2 \times 22 \times 24 = 1{,}056 \text{ ft.}$$

Thus, the west 80 acres of the field could be supplied by three manifolds, but the east half would need two manifolds.

iv) Construction was simplified and improved by selecting six equally spaced manifolds so that

$$S_m = 27 \times 24 = 648 \text{ ft.}$$

Thus, l will be 324 ft, and the head difference along each pair of laterals can be estimated by again using the 14.26-ft head loss computed for a 648-ft-long lateral in equation 7–65a.

$$h_f \cong 14.24\left(\frac{324}{648}\right)^{2.75}$$
$$h_f \cong 2.1 \text{ ft.}$$

Graphical determination of manifold position and $\triangle h$.—$J' = 6.11$ ft/100 ft, $F = 0.36$; $S = 0.5\%$, so $\frac{\triangle El}{L/100} = 0.5$; $\triangle H_s = 16.05$ ft; $J'F = 2.20$ ft/100 ft, $L/100 = 6.48$ ft.

i) Now compute J'F for a single lateral equal in length to the manifold spacing (S_m).

This was already done (see previous section, Manifold spacing [S_m], part ii, for l = 648 ft, in which

$$J'F = 6.11 \times 0.36 = 2.20).$$

Thus, 10 on the vertical scale of the overlay represents $J'F = 2.20$.

ii) Place an overlay on figure 7–31 and trace the friction curve (solid line) and the vertical lines on both the right and left sides of the figure, as shown in figure 7–46.

For use of the 0-to-10 dimensionless scale, values from a specific problem must be multiplied by (10/J'F).

iii) Next, draw a line representing the ground surface on the overlay. The left end of this ground-surface line should pass through zero on the vertical scale at x/L = 0 and the right end (at x/L = 1) should pass through

$$\left(\frac{\triangle El}{L/100}\right)' = \frac{10}{2.20} \times 0.5 \qquad (7\text{–}66)$$

$$\left(\frac{\triangle El}{L/100}\right)' = 2.27,$$

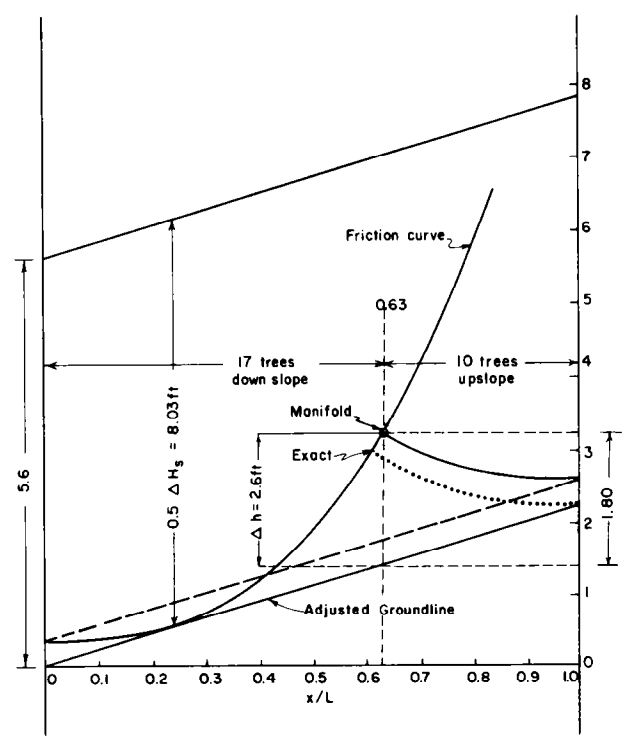


Figure 7–46.—Friction curve overlay to demonstrate graphical solution of manifold positioning and $\triangle h$ (difference in pressure head along the lateral). $\triangle H_s$ = allowable subunit pressure-head variation; x = position of manifold along lateral; L = length of lateral.

on figure 7–32, as shown by the dashed sloped line on figure 7–46.

Draw a line parallel to the groundline and tangent to the friction curve. Make sure this line intersects both vertical axes. This is the adjusted groundline, which is the solid straight line on figure 7–46.

A reasonable maximum allowable difference in pressure head along the pair of laterals is 0.5 $\triangle H_s$, as discussed earlier. This is represented by a line parallel to and above the adjusted groundline on the overlay. To represent this allowable pressure head, plot a line the following distance (number of units) above the adjusted groundline as shown in figure 7–46.

$$\text{Units} = \frac{10}{2.2}\left(\frac{0.5 \times 16.05}{6.48}\right) = 5.6$$

iv) To locate the best manifold position, move the overlay down on figure 7–31 until the dashed friction curve coincides with the adjusted groundline at x/L = 1.0.

v) This "exact" manifold position is at x/L = 0.61, where the dashed friction curve intersects the friction curve on the overlay as shown on figure 7–46. This position falls between the 16th and 17th trees from the lower end of the downslope lateral:

at 16 trees,

$$x/L = \frac{16 \times 24}{648} = 0.59,$$

and at 17 trees,

$$x/L = \frac{17 \times 24}{648} = 0.63.$$

The pressure at the upper end of the upslope lateral can be kept above the adjusted groundline by placing the manifold with 17 trees on the downslope laterals and 10 trees on the upslope laterals. To represent this manifold position, move the overlay so that the upslope (dotted) friction curve crosses the friction curve on the overlay at x/L = 0.63 as shown by the solid line in figure 7–46.

vi) The maximum variation in pressure head ($\triangle h$) along the pair of laterals is represented by the maximum distance that the upslope and downslope curves are above the adjusted groundline. Taking values from the overlay for the manifold at x/L = 0.63 and allowing for the scale factor:

$$\frac{\triangle h}{L/100} = \frac{2.20}{10} \times 1.80 \qquad \textbf{(7–66)}$$
$$\frac{\triangle h}{L/100} = 0.40,$$

and

$$\triangle h = 0.40 \times 6.48$$
$$\triangle h = 2.6 \text{ ft.}$$

vii) Because uniform manifold spacings have been chosen and the field has a uniform slope, the manifold position and the head loss in the average lateral, $\triangle h$ = 2.6 ft, will be the same for each subunit.

Numerical determination of manifold position and $\triangle h$.—J = 5.73 ft/100 ft, J′ = 6.11 ft/100 ft, F = 0.36, S = 0.5%; J = 0.5 ft/100 ft, J′F = 2.20 ft/100 ft; x/L = 17 trees/27 trees = 0.63, L/100 = 6.48 ft.

i) Determine J′F as in step 1 of the graphical solution.

ii) Find the tangent location (Y) by

$$Y = (0.5/6.11)^{1/1.75} \qquad \textbf{(7–67)}$$
$$Y = 0.24.$$

iii) Next, solve for the unusable slope component (S′) (see figure 7–34):

$$S' = (0.5 \times 0.24) - 2.20(0.24)^{2.75} \qquad \textbf{(7–68)}$$
$$S' = 0.08.$$

iv) The manifold position can now be located by satisfying equation 7–69. To satisfy the equation, first determine the term on the left:

$$\frac{S - S'}{J'F} = \frac{0.5 - 0.08}{2.20} = 0.19,$$

and then by trial and error find the x/L that balances the equation, i.e.:

$$(0.62)^{2.75} - (1 - 0.62)^{2.75} = 0.20.$$

v) The value of x/L = 0.62 falls between the 16th and 17th trees from the lower end. Thus, as discussed earlier, the manifold should be located to supply 17 trees along the downslope laterals and 10 trees along the upslope laterals.

vi) The maximum pressure-head variation ($\triangle h$) along the pair of laterals can be determined from equation 7–70 by use of the x/L value that represents the actual manifold location selected:

$$\triangle h = 6.48[2.20(0.63)^{2.75} + 0.08 - (0.5 \times 0.63)]$$
$$\triangle h = 2.5 \text{ ft.}$$

To check for the possibility that the maximum $\triangle h$ may occur at the closed end of the downslope lateral, determine

$$\triangle h_c = 0.08 \times 6.48 \qquad \textbf{(7–71a)}$$
$$\triangle h_c = 0.5 \text{ ft.}$$

Lateral inlet pressure head (h_l).—h_a = 44.65 ft, h_{fp} = 14.26 ft, z = x/L = 0.63, $\triangle El$ = 3.24 ft.

For pairs of laterals with a constant diameter, the lateral inlet pressure can be determined by equation 7–63a as

$$h_l = 44.65 + 0.75(14.26)[(0.63)^{3.75} + (1 - 0.63)^{3.75}] - (3.24/2)[2(0.63) - 1]$$
$$h_l = 44.65 + 2.15 - 0.42 = 46.4 \text{ ft.}$$

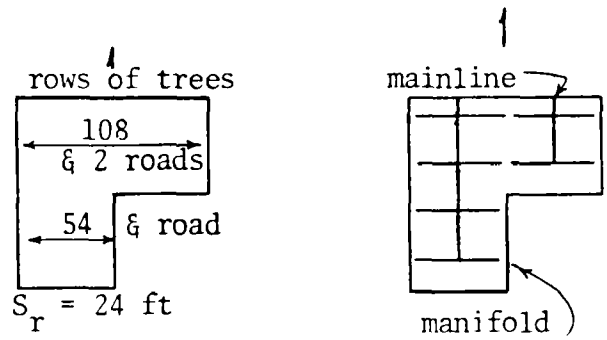
Manifold Design

Selecting pipe size for tapered manifolds involves three criteria:

1. A balance between the pipe's initial cost and the pumping cost over the pipe's expected life (described under Pipeline Hydraulics).
2. A balance between friction loss, change in elevation, and allowable variation in pressure.
3. Maximum permissible velocity.

Pipe sizes selected on the basis of economics are considered acceptable if variations in pressure do not exceed allowable limits. If limits of pressure variation are exceeded, the manifold is tapered by balancing the allowable limit with pipe friction and change in elevation. However, the maximum permissible velocity controls minimum pipe size regardless of the other criteria.

Manifold length and main-line position.



i) For economic reasons and for acceptable $\triangle H$, pairs of manifolds extending in opposite directions from a common main-line connection normally should not exceed a total length of 1,500 ft. Therefore, parallel main lines are needed.

ii) Main lines should be positioned so that starting from a common main-line connection, the minimum pressure in a pair of manifolds is equal (like the manifold position for pairs of laterals as discussed earlier). Because the ground is level in the direction of the laterals, the pair of laterals should be of equal length.

iii) There are access roads in place of the center row of trees in the west 80 acres and in the east 40 acres. Therefore, the length of each manifold is

$$L_m = 27 \times 24 = 648 \text{ ft.}$$

Manifold flow rate (q_m).—q_l = 1.0 gpm, and for a pair of laterals, q_{lp} = 2.0 gpm.

The manifold flow rate is the number of pairs of laterals along each manifold times the flow rate per pair:

$$q_m = 27 \times 2.0 = 54 \text{ gpm.}$$

Economic-chart method of manifold design.—Q_t = 2,686 hr, P_{uc} = \$0.0436/kWh, CRF = 0.205 (20% for 20 yr), EAE = 1.594 (9% inflation), E_p = 75%; BHP/P_u = 1.2 BHP-hr/kWh (taking into consideration the motor transformer and line deficiencies, a power conversion factor of 1.2 is reasonable); P_c = 1.00, Q_s = 54 gpm; q_m = 54.0 gpm, q_{lp} = 2.0; L_m = 648 ft; $\triangle H_s$ = 16.05 ft; $\triangle h'$ = 2.6 ft, from the graphical solution for lateral lines;

$l_1 = 648$ ft, $l_2 = 552$ ft, $l_3 = 240$ ft, $l_4 = 120$ ft;
$q_1 = 54.0$ gpm, $F_1 = 0.38$, $q_2 = 46.0$ gpm, $F_2 = 0.38$,
$q_3 = 20.0$ gpm, $F_3 = 0.41$, $q_4 = 10.0$ gpm, $F_4 = 0.47$.

i) All manifolds in the system serve similar areas, and extra pressure head can be used to reduce sizes of the pipe in all of these.

Therefore, the manifold flow rate (q_m) will be adjusted and used as the adjusted system flow (Q_s') to select the most economical pipe sizes.

ii) First compute the cost per water horsepower per season by equation 7–57:

$$C_{whp} = \frac{2{,}686 \times 0.0436 \times 1.594}{(75/100)(1.2)}$$

$$C_{whp} = \$207/\text{whp per year.}$$

iii) Determine the adjustment factor (A_f) to adjust Q_s to Q_s' for entering the proper unit economic pipe-size selection chart:

$$A_f = \frac{0.001 \times 207}{0.205 \times 1.00} = 1.01, \qquad \textbf{(7–58)}$$

and

$$Q_s' = 1.01 \times 54 \qquad \textbf{(7–59)}$$

$$Q_s' = 55 \text{ gpm.}$$

iv) The maximum pressure in this and most other typical trickle systems is less than 100 psi. Thus PVC pipe with the minimum available (or allowable) pressure rating can be used. Figure 7–33 is the unit economic pipe-size selection chart for this set of PVC pipe sizes.

Enter the vertical axis of figure 7–33 with $Q_s' = 55$ gpm. Record the flow rate (horizontal axis) where the 55-gpm line intersects the upper limit of each pipe size region, which is:

Pipe size	Chart flow rate	Adjusted[1] flow rate	Number of outlets
	gpm	gpm	
1¼-in.	10.5	$q_4 = 10.0$	5
1½-in.	20.2	$q_3 = 20.0$	10
2-in.	45.0	$q_2 = 46.0$	23
2½-in.	54.0	$q_1 = 54.0$	27

[1]Flow rates adjusted for nearest whole number of lateral connections.

v) Compute the length of pipe of each size, assuming uniform outlet discharge along the entire length of the manifold by:

$$L_{1\frac{1}{4}} = \frac{10.0 - 0}{54.0} \times 648 = 120 \text{ ft} \qquad \textbf{(7–78)}$$

$$L_{1\frac{1}{2}} = \frac{20.0 - 10.0}{54.0} \times 648 = 120 \text{ ft}$$

$$L_2 = \frac{46.0 - 20.0}{54.0} \times 648 = 312 \text{ ft}$$

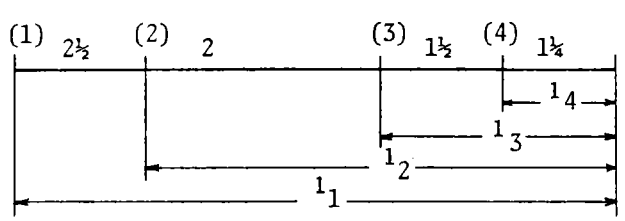
$$L_{2\frac{1}{2}} = 648 - (120 + 120 + 312) = 96 \text{ ft}$$

vi) Determine the allowable difference in manifold pressure head:

$$(\triangle H_m)_a = 16.05 - 2.6 = 13.5 \text{ ft,} \qquad \textbf{(7–73)}$$

and check this against $\triangle H_m$. To do this, first determine the head loss from pipe friction (H_f), and because there is no slope along the manifold, $H_f = \triangle H_m$ equals the friction loss along the manifold $[(h_f)_m]$.

The numerical method for determining H_f is as follows:



$$H_f = (h_f)_{2\frac{1}{2}} + (h_f)_2 + (h_f)_{1\frac{1}{2}} + (h_f)_{1\frac{1}{4}}.$$

For 2½-in., $J_1 = 1.36$, $J_2 = 1.02$, and

$$(h_f)_{2\frac{1}{2}} = \frac{1}{100}(J_1F_1l_1 - J_2F_2l_2)$$

$$= \frac{1}{100}[(1.36 \times 0.38 \times 648) - (1.02 \times 0.38 \times 522)]$$

$$(h_f)_{2\frac{1}{2}} = 1.21 \text{ ft.}$$

For 2-in., $J_2 = 2.55$, $J_3 = 0.58$, and

$$(h_f)_2 = \frac{1}{100}(J_2F_2l_2 - J_3F_3l_3)$$
$$= \frac{1}{100}[(2.55 \times 0.38 \times 552) - (0.58 \times 0.41 \times 240)]$$
$$(h_f)_2 = 4.78 \text{ ft.}$$

For 1½-in., $J_3 = 1.69$, $J_4 = 0.50$, and

$$(h_f)_{1\frac{1}{2}} = \frac{1}{100}(J_3F_3l_3 - J_4F_4l_4)$$
$$= \frac{1}{100}[(1.69 \times 0.41 \times 240) - (0.50 \times 0.47 \times 120)]$$
$$(h_f)_{1\frac{1}{2}} = 1.38 \text{ ft.}$$

For 1¼-in., $J_4 = 0.95$ and

$$(h_f)_{1\frac{1}{4}} = \frac{1}{100}(J_4F_4l_4)$$
$$= \frac{1}{100}(0.95 \times 0.47 \times 120)$$
$$(h_f)_{1\frac{1}{4}} = 0.54 \text{ ft.}$$

The field is level, so $H_f = \triangle H_m$ and

$$\triangle H_m = (h_f)_{2\frac{1}{2}} + (h_f)_2 + (h_f)_{1\frac{1}{2}} + (h_f)_{1\frac{1}{4}}$$
$$= 1.21 + 4.78 + 1.38 + 0.54$$
$$\triangle H_m = 7.91 \text{ ft.}$$

The graphical method for determining H_f is as follows:

Because the flow rate per outlet along the manifold (q_l) = 2.0 gpm, use figure 7–36 to make the overlay figure 7–47 as described in step 6b of the Economic-Chart Design Method under Manifold Design.

The scale factor for converting graph values plotted from figure 7–36 is

$$k = 648/54(0.1) = 1.2 \qquad \textbf{(7–79a)}$$

Therefore, by equation 7–80,

$$H_f = 1.2(6.6) = 7.9 \text{ ft,}$$

which is almost identical with the value obtained numerically.

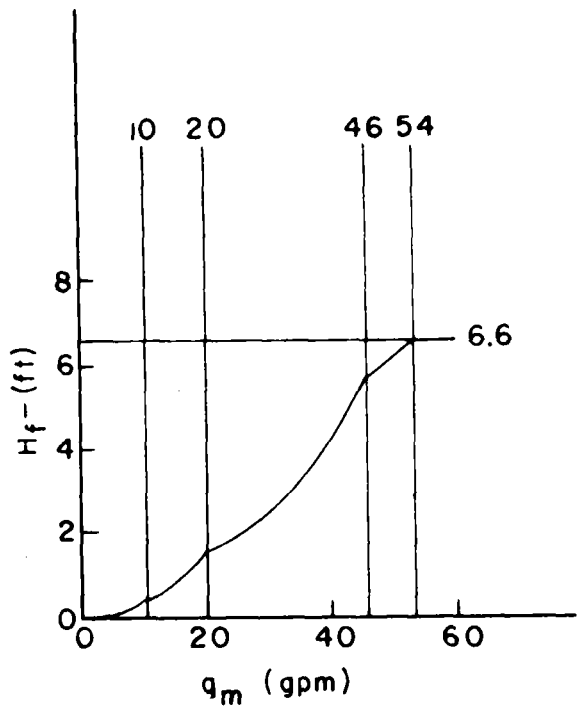


Figure 7–47.—Friction curve overlay to demonstrate graphical solution for determining manifold friction loss (H_f) for a drip system. q_m = manifold flow rate.

This value is less than $(\triangle H_m)_a = 13.5$ ft. Therefore pipe sizes selected by economic criteria are acceptable.

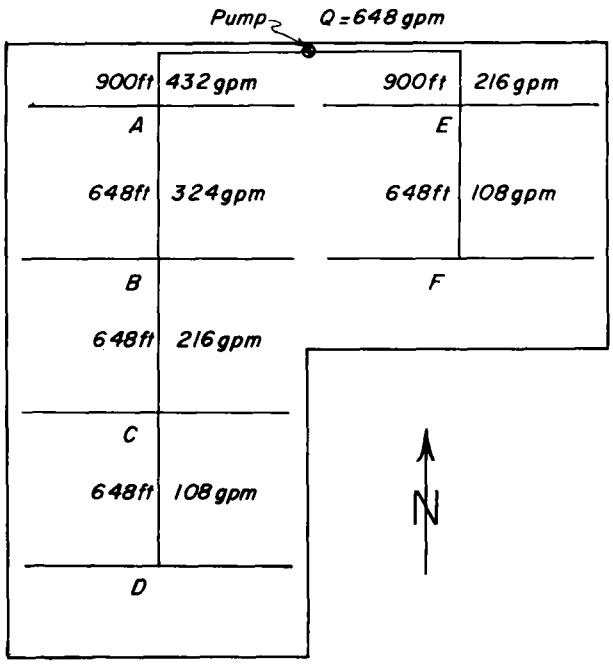
Manifold inlet pressure (H_m).—$h_l = 46.4$ ft, $\triangle H_m = 7.9$ ft; $\triangle H'_m = 0.5H_f + 0.5\triangle El$, $\triangle H'_m = (0.5)(7.9) + 0$, $\triangle H'_m = 4.0$.

$$H_m = 46.4 + 4.0 = 50.4 \text{ ft} \qquad \textbf{(7–76a)}$$

Main-Line Design

Selecting pipe size for main lines is based on economic, pressure, and velocity criteria. After the initial pipe sizes are selected from an economic chart, additional savings are often possible in branching systems by reducing pipe sizes along specific branches to the limits imposed by pressure or velocity criteria. In such cases, sizes may be reduced to take advantage of any excess pressure head that might result from differences in elevation or from higher pressures required for other branches of the system.

Economic pipe-size selection.—Q_s = 432 gpm, A_f = 1.01.



i) First sketch the main-line layout, indicating lengths of pipe and rates of flow along the various sections of pipe.

ii) The unit economic pipe-size selection chart, figure 7–33, is used to select the first set of main-line pipe sizes. Because the flow is divided immediately after the pump, the larger of the two branch flow rates must be adjusted for entering the chart:

$$Q_s' = 1.01 \times 432 \qquad \textbf{(7–59)}$$
$$Q_s' = 436 \text{ gpm.}$$

iii) Enter the vertical axis of figure 7–33 with 436 gpm and determine the most economical size of PVC pipe for each flow section. To hold velocities below 5 ft/s, stay within the solid boundary lines. After selecting the minimum pipe sizes, determine the friction loss in each section as shown in the following table based on equation 7–52.

Sect.	Flow (gpm)	Pipe (in.)	J'	$\frac{L}{100}$	h_f (ft)
P–A	432	6	0.90	9.00	8.10
A–B	324	6	0.54	6.48	3.50
B–C	216	6	3.26	6.48	1.68
C–D	108	4	0.47	6.48	3.05
P–E	216	6	0.26	9.00	2.34
E–F	108	4	0.47	6.48	3.05

Location of critical manifold inlet.

i) Compute the pressure head required to overcome pipe friction and elevation difference $(H_{fe})_m$ between the pump and each manifold inlet point by using equation 7–60 as follows:

Point	From–to	Inlet (ft)	+	Section H_f (ft)	±	ΔEl (ft)	=	Point $(H_{fe})_m$ (ft)
A	P–A	P=0	+	8.10	–	1.20	=	6.90
B	A–B	6.90	+	3.50	–	3.24	=	7.16[1]
C	B–C	7.16	+	1.68	–	3.24	=	5.60
D	C–D	5.60	+	3.05	–	3.24	=	5.41
E	P–E	P=0	+	2.34	–	1.20	=	1.14
F	E–F	1.14	+	3.05	–	3.24	=	0.95

[1]Critical.

ii) The $(H_{fe})_m$ values in (i) show that the critical manifold inlet is at point B, and the pump must supply $(H_{fe})_m$ = 7.16 ft to overcome pipe friction and elevation along the main lines. Because the manifolds require the same inlet pressure head, if the required H_m = 50.4 ft is supplied at point B, all other requirements for manifold inlet pressure head will be more than satisfied.

iii) Furthermore, the above $(H_{fe})_m$ values clearly show that the pipe sizes in sections B–C and P–E can be reduced or trimmed without increasing the system head requirements.

Reducing main-line pipe size.—$(H_{fe})_m$ = 7.16 ft, $(H_{fe})_C$ = 5.60 ft; J_4 = 1.65, J_6 = 0.26; $(H_{fe})_D$ = 5.41 ft before tapering section B–C; $(H_{fe})_E$ = 1.14 ft before tapering section P–E; J_4 = 1.65, J_6 = 0.26, L_{P-E} = 900 ft.

i) The pipe sizes between the pump and the critical manifold inlet cannot be trimmed without increasing the pump head requirements. However, the pipe sections downstream from the critical inlet point and along other branches can be trimmed so that the corresponding manifold inlet points also require $(H_{fe})_m$ = 7.16 ft.

ii) The gain in pressure head between B and C is:

$$(\triangle H)_{B-C} = 7.16 - 5.60 = 1.56 \text{ ft}$$

This unnecessary gain in pressure head can be eliminated to reduce pipe costs by replacing some of the 6-in. pipe with 4-in. pipe in section B–C. The exact length of the smaller pipe (L_s) that will increase the head loss by $\triangle H$ is

$$(L_4)_{B-C} = \frac{(\triangle H)_{B-C}}{J_4 - J_6} \times 100 \qquad \textbf{(7-61)}$$

$$= \frac{1.56 \times 100}{1.65 - 0.26}$$

$$(L_4)_{B-C} = 112 \text{ ft.}$$

iii) With 536 ft of 6-in. and 112 ft of 4-in. pipe in section B–C, the H_{fe} at point C will increase to the system $(H_{fe})_m = 7.16$ ft. The $(H_{fe})_m$ will also increase by 1.56 ft at point D, which gives $(H_{fe})_D = 6.97$ ft. This value is so close to the system $(H_{fe})_m$ that further tapering would require a short length of 3-in. pipe, which might actually increase the system cost because of the additional pipe size, extra fittings, and more complicated construction.

iv) Using the same logic and procedures along the east branch of the system, for $(H_{fe})_m = 7.16$ ft, the friction loss in the 6-in. pipe between P and E can be increased by

$$(\triangle H)_{P-E} = 7.16 - 1.14 = 6.02 \text{ ft,}$$

and the length of 4-in. pipe taper in section P–E from equation 7–61 should be

$$(L_4)_{P-E} = \frac{6.02 \times 100}{1.65 - 0.26}$$

$$(L_4)_{P-E} = 433 \text{ ft.}$$

So the remaining length of 6-in. pipe in section P–E should be

$$(L_6)_{P-E} = 900 - 433 = 467 \text{ ft.}$$

Total Dynamic Head

The total dynamic head (TDH) required of the pump is the sum of the following:

Item		ft
(1)	Manifold inlet pressure head ..... H_m =	50.4
(2)	Pressure head to overcome pipe friction and elevation along the main line. H_{fe} =	7.2
(3)	Suction friction loss and lift	10.0[1]
(4)	Filter—maximum pressure-head differential	23.1[2]
(5)	Valve and fitting friction losses:	
	Fertilizer injection	—[3]
	Flow meter	3.0[4]
	Main control valves	0.5[4]
	Manifold inlet valve and pressure regulator	6.9[4]
	Lateral risers and hose bibs	2.3[4]
	Safety screens at manifold or lateral inlets	2.3[4]
	Lateral or header pressure regulators ..	—[5]
(6)	Friction-loss safety factor at 10 percent ..	6.6[6]
(7)	Additional pressure head to allow for deterioration of emitters	—[7]
Total		112.3

[1]Assumed value that includes suction screen, friction in suction pipe and foot valve, and elevation from water surface to pump discharge.

[2]Automatic back-flushing filter to be set to flush when pressure differential reaches 10 psi.

[3]Injection pump used.

[4]Taken from manufacturer's or standard charts.

[5]Not used in this system.

[6]Friction-loss safety factor taken as 10 percent of lateral (2.1 ft), manifold (7.9 ft), main line (18.0 ft), and filter (23.1 ft), plus friction losses from valves and fittings.

[7]The flow characteristics of the vortex emitters used in this design are not expected to change with time.

System Design Summary

The final system-design layout is shown in figure 7–44. The design data are presented in figures 7–43 and 7–45. These three figures, along with a brief writeup of the system specifications and a bill of materials, form the complete design package.

For scheduling irrigation, the emission uniformity, the net system application rate, and the peak daily net system application should be:

Final emission uniformity (EU).—$x = 0.42$, $H_m = 50.4$ ft, $\triangle H_m = 7.87$ ft, $\triangle h = 2.68$ ft, $h_a = 44.65$ ft; $e' = 4$, $v = 0.07$.

i) Compute the ratio of minimum emitter discharge to average emitter discharge in a subunit by equations 7–38 and 7–39:

$$q_n/q_a = \left[\frac{50.4 - 7.9 - 2.7}{44.6}\right]^{0.42}$$

$$q_n/q_a = 0.95.$$

ii) Assuming all the manifolds to be adjusted to the same inlet pressures, final or actual expected system EU will be

$$EU = 100(1 - \frac{1.27}{\sqrt{4}}[0.07])0.95 \quad \textbf{(7-33a)}$$
$$EU = 91\%.$$

Net application rate (F_n).—S_p = 24 ft, S_r = 24 ft, e = 4, q_a = 1.11 gph, EU = 93%.

$$F_n = 1.604 \times \frac{93}{100} \frac{(4 \times 1.11)}{(24 \times 24)} \quad \textbf{(7-40)}$$
$$F_n = 0.0115 \text{ in./hr}$$

Maximum net daily application rate (F_{mn}).—After a breakdown, the system may be operated 24 hr/day to make up for lost irrigation time. The maximum net daily application rate is

$$F_{mn} = 0.0115 \times 24 = 0.28 \text{ in.}$$

Spray System

The following spray design is for a typical citrus grove. The data that should be collected before beginning a design are summarized in the trickle irrigation design sheet, figure 7–48, and the field layout map, figure 7–49.

In addition to illustrating the general process for designing a spray irrigation system, the example emphasizes the following procedures:

1. Manifold spacing for multistation systems.
2. Economic pipe sizing for tapered manifolds (both graphical and adjusted economic-chart method solutions) on a rectangular field.
3. Pipe sizing for tapered manifolds on a nonrectangular field.

Sample design computations developed under Drip System are presented more briefly in this section.

Design Factors

The values obtained for the spray design factors are presented in figure 7–50. Details for computing most of these values, except the percent area wetted, have already been presented under Drip System.

The particular spray emitter selected wets a "butterfly"-shaped pattern that can be approximated by a circle with two 40° pie-shaped wedges cut out. The wedges are opposite each other and result from water being deflected by supports that hold a deflection cap above a vertical nozzle. The diameter of the wetted circle and the nozzle's discharge are both functions of the operating pressure. From information provided by the manufacturer, the emitter exponent and coefficient of discharge are x = 0.556 and k_d = 1.89, respectively, and the relation between pressure and wetted diameter is plotted as shown in figure 7–51.

Percent area wetted (P_w).—Diameter of surface area taken from figure 7–50 is 14.5 ft; for fine sandy (coarse)-textured soil, s_e' = 2.0 ft; e = 1, S_p = 15 ft, S_r = 25 ft.

i) The surface area (A_s) wetted directly by the spray at the rated pressure of 25 psi is

$$A_s = \frac{(14.5)\pi}{4} \times \frac{280}{360}$$
$$A_s = 128.43 \text{ ft}^2.$$

ii) The total wetted soil area is larger than the surface area wetted because there is some outward soil water movement, as shown in figure 7–20. The total wetted soil area can be estimated by adding one-half of the S_e' value for homogeneous soils taken from table 7–2 to the perimeter of the wetted surface soil (PS). For the "butterfly"-type wetting patterns, PS can be assumed equal to the circumference of the full circle.

$$PS = 14.5\pi = 45.55 \text{ ft.}$$

iii) From equation 7–3,

$$P_w = \frac{1[128 + (2.0/2 \times 46)]}{15 \times 25} \times 100$$
$$P_w = 46.40\%$$

This represents an acceptable design.

Computations for design.

i) $$F_{mn} = \frac{30}{100} \times 0.7 \times 6.0 \times \frac{46.40}{100} \quad \textbf{(7-4)}$$
$$F_{mn} = 0.58 \text{ in.}$$

ii) $$T_d = 0.25[\frac{75}{100} \times 0.15(1.0 - \frac{75}{100})] \quad \textbf{(7-5)}$$
$$T_d = 0.20 \text{ in./day}$$

iii) I_f = 0.58/0.20 = 2.9 days

I	Project Name--Florida Spray Design	Date-Fall 1978
II	Land and Water Resources	
	a) Field no.	#1
	b) Field area (acres), A	32.23
	c) Average annual effective rainfall (in.), R_e	39.0
	d) Residual stored soil moisture from off-season precipitation (in.), W_s	1.0
	e) Water supply (gpm)	Pit
	f) Water storage (acre-ft)	--
	g) Water quality (mmhos/cm), EC_w	0.3
	h) Water quality classification	Excellent
III	Soil and Crop	
	a) Soil texture	Fine sand
	b) Available water-holding capacity (in./ft), WHC	0.7
	c) Soil depth (ft)	10
	d) Soil limitations	None
	e) Management-allowed deficiency (%), M_{ad}	30
	f) Crop	Citrus
	g) Plant spacing (ft x ft), S_p x S_r	15 x 25
	h) Plant root depth (ft), RZD	6
	i) Percent area shaded (%), P_s	75
	j) Average daily consumptive-use rate for the month of greatest overall water use (in./day), u_d	0.25
	k) Season total crop consumptive-use rate (in.), U	48.0
	l) Leaching requirement (ratio), LR_t	0.02
IV	Emitter	
	a) Type	280° spray
	b) Outlets per emitter	1
	c) Pressure head (psi), h	25.0
	d) Rated discharge @ h (gph), q	11.3
	e) Discharge exponent, x	0.556
	f) Coefficient of variability, v	0.042
	g) Discharge coefficient, k_d	1.89
	h) Connection loss equivalent (ft), f_e	0.4

Figure 7–48.—Spray-system data for a citrus grove in Florida.

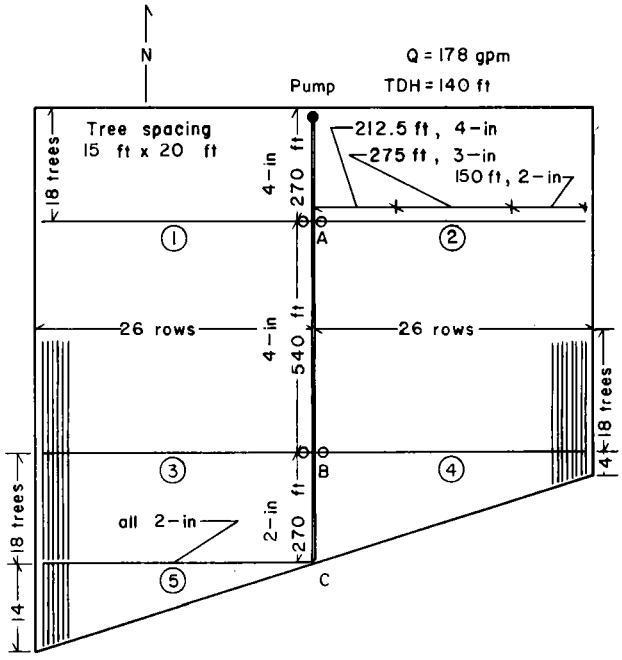


Figure 7–49.—Citrus grove with spray irrigation system. Lateral lines are 0.70-in. polyethylene and manifolds and main lines are polyvinyl chloride pipe.

iv) $F_n = 0.20 \times 1.0 = 0.20$ in. **(7–6)**

v) From table 7–4,

max $EC_c = 8$ mmhos

$$LR_t = \frac{0.3}{2(8)} = 0.02. \quad \textbf{(7–17)}$$

vi) $T_r = 1.00$, assumed EU = 90%.

$$F_g = \frac{0.20 \times 1.00}{90/100} = 0.22 \text{ in.} \quad \textbf{(7–8a)}$$

vii) $$F_{(gp/d)} = \frac{0.623 \times 0.22 \times 15 \times 25}{1} \quad \textbf{(7–9)}$$

$F_{(gp/d)} = 51.40$ gal/day

viii) $$T_a = \frac{51.40}{1.0 \times 11.3} = 4.55 \text{ hr/day} \quad \textbf{(7–30)}$$

Round off to 4.5 hr/day and use N = 4 to give 18 hr/day operation.

ix) From equation 7–30 (rearranged),

$$q_a = \frac{51.40}{1.0 \times 4.5} = 11.42 \text{ gph.}$$

x) $$h_a = \left(\frac{11.42}{1.89}\right)^{1/0.556} \quad \textbf{(7–31)}$$

$h_a = 25.41$ psi or 58.70 ft.

xi) From equation 7–33a (rearranged),

$$q_n = \frac{11.42 \times 90/100}{1.0 - (0.042 \times 1.27\sqrt{1.0})}$$

$q_n = 10.86$ gph.

By equations 7–31 and 7–38,

$$h_n = \left(\frac{10.86}{1.89}\right)^{1/0.556} = 23.20$$

$$\triangle H_s = 2.5(25.41 - 23.20) \quad \textbf{(7–34)}$$

$\triangle H_s = 5.53$ psi or 12.76 ft.

xii) $$Q_s = 726 \times \frac{32.23}{4} \times \frac{11.42}{15 \times 25} \quad \textbf{(7–35)}$$

$Q_s = 178$ gpm.

Seasonal irrigation efficiency (E_s).—EU = 90%, $LR_t = 0.02$.

i) Entering table 7–3 midway between the coarse and very coarse soil-texture columns for humid zones and for root depth over 5 ft plus 0.05 for spray emitters gives

$T_R = 1.20$.

ii) Because $T_R \geq 1/(1.0 - LR_t)$, i.e., $1.20 \geq 1/(1 - 0.02) = 1.02$, use equation 7–12 to compute E_s as

$$E_s = \frac{90}{1.20(1.0 - 0.02)}$$

$E_s = 76.5\%$.

Gross seasonal volume (V_i).—U = 48.0 in., R_e = 39.0 in., W_s = 1.0 in., $U - R_e - W_s$ = 8.0 in.

i) The annual net depth of application from equation 7–10 is

$$F_{an} = 8.0\left[\frac{75}{100} + 0.15\left(1.0 - \frac{75}{100}\right)\right]$$

$F_{an} = 6.3$ in.

ii) From equation 7–14,

I	Project Name--Florida Spray Design	Date-Fall 1978
II	Trial Design	
a)	Emission point layout	St. line
b)	Emitter spacing (ft x ft), S_e x S_l	15 x 25
c)	Emission points per plant, e	1
d)	Percentage area wetted (%), P_w	46.40
e)	Maximum net depth of application (in.), F_{mn}	0.58
f)	Ave. peak transpiration rate (in./day), T_d	0.20
g)	Maximum allowable irrigation interval (days), I_f	2.9
h)	Design irrigation interval (days), I_f	1
i)	Net depth of application (in.), F_n	0.20
j)	Emission uniformity (%), EU	90
k)	Gross water application (in.), F_g	0.22
l)	Gross volume of water required per plant per day (gal/day), $F_{(gp/d)}$	51.40
m)	Time of application (hr/day), T_a	4.55
III	Final Design	
a)	Time of application (hr/day), T_a	4.50
b)	Design irrigation interval (days), I_f	1.0
c)	Gross water application (in.), F_g	0.22
d)	Average emitter discharge (gph), q_a	11.42
e)	Average emitter pressure head (ft), h_a	58.70
f)	Allowable pressure-head variation (ft), ΔH_s	12.75
g)	Emitter spacing (ft x ft), S_e x S_l	15 x 25
h)	Percent area wetted (%), P_w	46
i)	Number of stations, N	4
j)	Total system capacity (gpm), Q_s	178
k)	Seasonal irrigation efficiency (%), E_s	76.5
l)	Gross seasonal volume (acre-ft), V_i	22.0
m)	Seasonal operating time (hr), Q_t	689
n)	Total dynamic head (ft), TDH	140
o)	Actual uniformity (%), EU	90
p)	Net water-application rate (in./hr), F_n	0.044

Figure 7–50.—Spray-system design factors for a citrus grove in Florida.

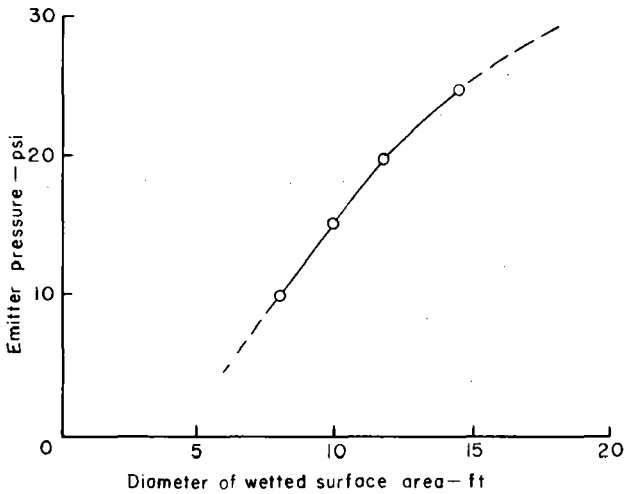


Figure 7-51.—Plot of spray diameter vs. emitter pressure developed from manufacturer's data for 0.04-in.-diameter orifice.

$$V_i = \frac{6.3 \times 32.23}{12(76.5/100)(1 - 0.02)}$$
$$V_i = 22.6 \text{ acre-ft.}$$

iii) From equation 7-37,

$$Q_t = \frac{5{,}430 \times 22.6}{178}$$
$$Q_t = 689 \text{ hr.}$$

Lateral Line Design and System Layout

Lateral-line design procedures are essentially the same for drip and spray irrigation systems. The design procedure includes determining the manifold spacing, the manifold layout, and the maximum pressure-head variation along the laterals.

Manifold spacing (S_m).—S_p = 15 ft; l = 270 ft, $S_e = S_p$ = 15 ft, q_a = 11.43 gph; J = 14.69 from Appendix B, F = 0.39 from table 7-6, f_e = 0.5 ft from figure 7-20; $\triangle H_s$ = 12.76 ft; J = 6.01, f_e = 0.4.

i) There must be at least one manifold for each of the four stations (N = 4) determined in the design factor computations.

The tree rows run north and south, and there is no dominant slope. Therefore, the manifolds should run east and west. No adjustments in manifold position are necessary to compensate for slope effects.

ii) A main line can be placed running north-south midway between the east and west boundaries of the grove. There are 52 rows of trees with an average of 72 trees per row. Two pairs of manifolds plus a fifth manifold for the small triangular section in the southwest corner can be laid out to divide the field into four equal stations, as shown in figure 7-49.

iii) The spacing between the pairs of manifolds and the length of laterals in the rectangular sections is

$$S_m = (72 \times 15)/2 = 540 \text{ ft.}$$

iv) The pressure head difference ($\triangle h$) for the level laterals having 0.58-in. hose and serving 18 trees to either side of each manifold is

$$q_l = \frac{270}{15}\,\frac{11.43}{60} \qquad \textbf{(7-62)}$$
$$q_l = 3.43 \text{ gpm.}$$

From equations 7-51b and 7-52,

$$J' = 14.69\frac{15 + 0.5}{15} = 15.18 \text{ ft/100 ft,}$$

and

$$h_f = 15.18 \times 0.39 \times 270/100$$
$$h_f = 15.98 \text{ ft.}$$

v) This exceeds $0.5\triangle H_s$ = 6.38 ft. Either the laterals must be shortened or larger diameter pipe used. For $h_f \leq$ 6.38 ft, the maximum length of a 0.58-in.-diameter lateral by equation 7-65b is

$$l_b = 270\left(\frac{6.38}{15.98}\right)^{1/2.75} = 193.36 \text{ ft.}$$

This requires dividing the field to operate with either three or six stations. Neither arrangement is satisfactory, because three stations would operate only 13.5 hr/day and six stations would operate 27 hr/day.

vi) Repeating part (iv) with 0.7-in. hose gives

$$J' = 6.01\left(\frac{15 + 0.4}{15}\right) = 6.17 \text{ ft/100 ft}$$
$$h_f = 6.17 \times 0.39 \times 270/100$$
$$h_f = 6.50 \text{ ft.}$$

This is close enough to 6.38 ft to be acceptable for the four-station layout shown in figure 7–49.

Manifold layout.

i) Because the field is nearly level, the manifolds should be laid out to serve laterals of equal length on both sides (except in the triangular areas), as shown in figure 7–49.

ii) The operating sequence for the four stations is:

Station	Manifold	Q_s (gpm)
I	(1)	178
II	(2)	178
III	(3)	178
IV	(4 & 5)	144 + 34 = 178

The flow rates are perfectly balanced as all stations require the same Q_s = 178 gpm.

Maximum variation of lateral pressure head ($\triangle h$).—Because the field is nearly level, $\triangle h = h_f$ = 6.50 ft.

Lateral inlet pressure head (h_l).—$\triangle El$ = 0.0 ft, h_a = 58.70 ft, h_f = 6.50 ft (for a single lateral).

For pairs of constant-diameter laterals on level fields, the lateral inlet pressure head can be determined by equation 7–63c, in which the h_f of one single lateral of the pair is known:

$$h_l = h_a + 3/4\ h_f + \frac{\triangle El}{2}$$
$$= 58.70 + 3/4\ (6.50)$$
$$h_l = 63.58 \text{ ft.}$$

Manifold Design

Typically, manifolds are tapered and should have no more than four pipe sizes, with the diameter of the smallest pipe no less than half that of the largest pipe. Manifold pipe size for rectangular subunits can be selected either by the economic-chart method or by the graphical method. For rectangular subunits both the economic-chart method and the alternative graphical method are quick, but only the general graphical method is suitable for tapered manifolds on trapezoidal subunits. In the following example, all three methods will be compared for the design of the rectangular subunits.

Manifold length and main-line position.—S_r = 25 ft, n_r = 52/2 = 26.

i) Because the field is nearly level, the main line should be placed in the center of the field and should supply equal-length manifolds to the east and west.

ii) Because there are 52 rows of trees across the field and no roadway (or missing tree row) along the main line, the manifold length (L_m) by equation 7–75 is

$$L_m = 25(26 - 1/2) = 637.5 \text{ ft.}$$

Allowable manifold pressure-head difference [$(\triangle H_m)_a$].—$\triangle h$ = 6.50 ft, $\triangle H_s$ = 12.76 ft.

$$(\triangle H_m)_a = 12.76 - 6.50 \qquad \textbf{(7–73)}$$
$$(\triangle H_m)_a = 6.26 \text{ ft.}$$

Manifold flow rates (q_m).

Manifold	q_m (gpm)
(1)	178
(2)	178
(3)	178
(4)	144
(5)	34

Economic-chart method for rectangular subunits.—E_p = 75%, seasonal operation is 689 hr/year, P_{uc} = \$0.0436/kWh, BHP-hr/kWh = 1.2; from table 7–8, EAE = 1.594, CRF = 0.205 for n = 20 years and i = 20%, P_c = \$1.00/lb; q_l = 3.43 gpm, and for a pair of laterals, q_{lp} = 6.86 gpm; L_m = 637.5 ft, q_m = 178 gpm.

i) Details for using the economic pipe-size selection chart for manifold design are presented under Manifold Design, and an example of the computational procedure is presented under Drip System in Samples of Trickle Irrigation System Designs.

ii) An adjusted system flow rate (Q_s') must be computed for entering the economic pipe-size selection chart, figure 7–33. The steps to compute Q_s' are from equation 7–57:

$$C_{whp} = \frac{689 \times 0.0436 \times 1.594}{75/100 \times 1.2}$$
$$C_{whp} = \$53.20/\text{whp per year;}$$

and from equation 7–58:

$$A_f = \frac{0.001 \times 53.20}{0.205 \times 1.00}$$
$$A_f = 0.26.$$

For the rectangular subunits that are served by manifolds (1), (2), and (3), the system and manifold

flow rates are equal:

$$Q_s = q_m = 178 \text{ gpm}.$$

Therefore, from equation 7–77,

$$Q_s' = 0.26 \times 178 = 46 \text{ gpm}.$$

iii) Selecting the pipe sizes and computing the manifold pressure-head variation ($\triangle H_m$) gives

4-in.	112.5 ft
3-in.	300 ft
2½-in.	50 ft
2-in.	175 ft

and

$$\triangle H_m = H_f = 9.2 \text{ ft}.$$

iv) Because $\triangle H_m = 9.2$ ft exceeds $(\triangle H_m)_a = 6.26$ ft, the set of pipe sizes must be increased. The most economical mixture of pipe sizes that will give $\triangle H_m \cong 6$ ft can be obtained by modifying Q_s' and repeating the procedures used in step (iii).

The modified system flow rate, by equation 7–82a, is

$$Q_s'' = \frac{9.21}{6.26}(46) = 68 \text{ gpm}.$$

Enter figure 7–33 with 68 gpm to obtain:

Pipe size (in.)	Chart (gpm)	Adjusted (gpm)	Outlet no.
2	40	41	6
2½	50	48	7
3	120	117	17
4	178	178	26

The computed lengths by equation 7–78a and friction losses from figure 7–37 are:

Pipe size (in.)	Length (ft)	H_f (ft)	Weight (lb)
2	150	1.40	63
2½	25	0.28	15
3	250	2.94	186
4	212.5	1.92	209
Total	637.5	6.54	473

From equation 7–81a for the flat field, $\triangle H_m = H_f = 6.5$ ft. Valves within 10 percent of $(\triangle H_m)_a = 6.26$ ft are close enough so further adjustment is not required. When this calculated value of $\triangle H_m$ exceeds the 10-percent limit, the pipe sizes can be adjusted by inspection or another cut can be made by adjusting Q_s''.

v) Because there is very little 2½-in. pipe called for, replacing it with 3-in. pipe would probably be more economical. This would reduce the final pipe array to:

Pipe size (in.)	Length (ft)	H_f (ft)	Weight (lb)
2	150	1.40	63
3	275	3.05	204
4	212.5	1.92	209
Total	637.5	6.37	476

and

$$\triangle H_m = H_f = 6.4 \text{ ft}.$$

vi) An example of the graphical method for obtaining H_f is presented in figure 7–52. Because $q_{lp} = 6.86$ gpm, the standard manifold curves presented in figure 7–37 were used. By equation 7–79a,

$$k = (637.5/178)(0.1)$$
$$k = 0.36.$$

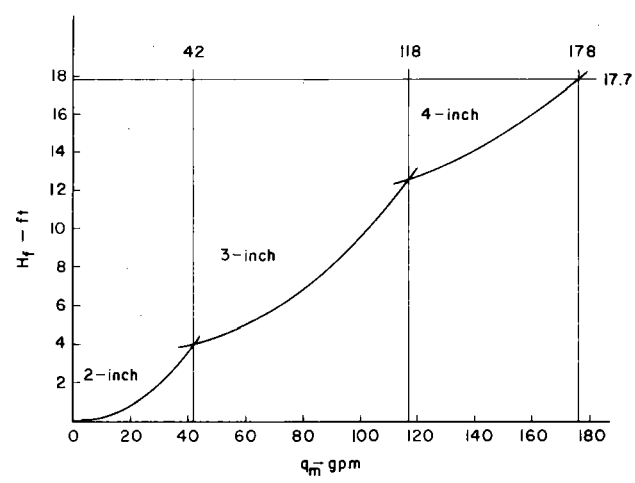


Figure 7–52.—Friction curve overlay to demonstrate graphical solution for determining manifold friction loss (H_f) for a spray system. q_m = manifold flow rate.

From figure 7–51, H_f = 17.7 ft, and by equation 7–80,

$$H_f = 0.36(17.7) = 6.37 \text{ ft.}$$

(For more details see figure 7–47 under Drip System.)

General graphical method, rectangular subunits.—From table 7–6, F = 0.38 for 26 outlets; because the subunit is rectangular, $S_f = 1$ by equation 7–83, $F_s = 1$ by equation 7–84, and $F' = F = 0.38$; $(\triangle H_m)_a = 6.26$ ft, $L_m = 647.5$ ft.

i) From the first trial of the economic-chart method, it is apparent that 4-, 3-, 2-1/2-, and 2-in. pipe should be considered.

ii) Determine the JF′ values for each of these pipe sizes for a flow rate of q_m = 178 gpm. Using J values from Appendix B:

Pipe size (in.)	J	JF′
4	1.17	0.42
3	4.19	1.59
2-1/2	11.60	4.41
2[1]	28.97	11.09

[1]The J value for the 2-in. pipe was estimated from the J = 28.09 given in Appendix B for the highest flow, at Q = 175 gpm, by

$$J = 28.09\left(\frac{178}{175}\right)^{1.8} \qquad (7\text{–}85)$$

iii) The rectangular units have a shape factor, $F_s = 1$. Therefore, the scalar JF′ ratios for plotting friction curves for the various-sized pipe are given in the middle column of table 7–9. To construct a dimensionless plot containing a set of curves scaled to represent each of the four sizes of pipe, multiply the scalar JF′ ratios from table 7–9 by the above JF′ values to obtain table 7–10.

iv) Plot x/L vs. the scaled JF′ values given in table 7–10, as shown in figure 7–39. The resulting curves are the dimensionless friction curves scaled for each pipe size under consideration.

v) Determine the dimensionless allowable head-loss ratio by equation 7–86:

$$j = \frac{(\triangle H_m)_a}{L_m/100} = \frac{6.26}{637.5/100} = 0.98.$$

This represents the allowable pipe-friction loss on the same proportional scale as the pipe friction curves of figure 7–39.

vi) Place a transparent overlay on figure 7–39 and trace the horizontal and vertical scales and boundaries, as shown on figure 7–40.

Draw a sloping line through the origin and through j = 0.98 at x/L = 1.0, then draw a second sloping line parallel to the first and passing through

$$0.9j = 0.9 \times 0.98 = 0.88$$

at x/L = 1.0, as shown by the dashed line on figure 7–40.

vii) The combination of pipe diameters and lengths that will give a solution close to the most economical solution with a $\triangle H_m$ = 6.26 ft will have a friction curve defined by the two sloping lines. The procedure for drawing the composite curve shown on figure 7–40 is given in the Manifold Design section (see step 8 of the General Graphical-Design Method).

viii) A summary of the general graphical design for manifolds (1), (2), and (3) is:

Pipe size (in.)	Length (ft)	Weight (lb)
2	118	50
2½	89	55
3	223	165
4	207.5	204
Totals	637.5	474

and $\triangle H_m = H_f = 6.3$ ft.

Notice that the total weight (and consequently the cost) of the pipe is essentially the same as determined by the economic chart method, but the lengths of the pipes of various sizes are somewhat different.

Alternative graphical method.—k = 0.36, $(\triangle H_m)_a = 6.26$ ft, q_m = 178 gpm.

i) In the alternative graphical method, figure 7–38 is used in place of constructing figure 7–39, and the method is applicable only for rectangular subunits. The alternative method saves the time required to construct figure 7–39.

ii) First compute j′ by equation 7–87 to properly scale $(\triangle H_m)_a$:

$$j' = \frac{6.26}{0.36} = 17.4 \text{ ft.}$$

iii) Following steps 6′, 7a′, and 8′ of the Alternative Graphical-Design Method under Manifold

Design, construct figure 7–42. This construction procedure is similar to the procedure that was used to produce figure 7–40.

iv) A summary of the alternative graphical design for manifolds (1), (2), and (3) is:

Pipe size (in.)	Flow range (gpm)	Length (ft)
2	0–28	100
2½	28–58	107.5
3	58–120	222
4	120–178	208
Total		637.5

and $\triangle H_m = H_f = 6.3$ ft.

A sample computation (for the length of 4-in. pipe) by equation 7–79 is

$$L_4 = \frac{(178 - 120)}{178} 637.5 = 208 \text{ ft.}$$

Graphical method, nonrectangular subunits.— From figure 7–44, for manifold (4) $(n_p)_c = 22$ plants and $(n_p)_a = (22 + 36)/2 = 29$ plants, for manifold (5) $(n_p)_c = 14$ plants and $(n_p)_a = (14 + 0)/2 = 7$ plants; $q_a = 11.43$ gph, $S_e = S_p$, $(q_l)_4 = (11.43 \times 29)/60$, $(q_l)_5 = (11.43 \times 7)/60$; $(S_f)_4 = 0.76$; from table 7–6, $F = 0.38$; $(F_s)_4 = 0.88$; $(q_m)_2 = 144$ gpm, $(q_m)_1 = 178$ gpm, $(F_s)_1 = 1.0$, $(F_s)_2 = 0.88$; $F' = 0.59$; from Appendix B, $J = 1.54$ for 34.67 gpm in 2-in. pipe.

i) Manifolds (4) and (5) serve nonrectangular subunits. For manifold (4), the shape factor is

$$(S_f)_4 = \frac{22}{29} = 0.76 \qquad \textbf{(7–83)}$$

and for manifold (5), it is

$$(S_f)_5 = \frac{14}{7} = 2.0.$$

ii) In manifold (4), which serves 26 tree rows, the flow rate is

$$(q_m)_4 = \frac{11.43 \times 29}{60} \times 26$$
$$(q_m)_4 = 143.64 \text{ gpm,}$$

and for manifold (5) it is

$$(q_m)_5 = \frac{11.43 \times 7}{60} \times 26$$
$$(q_m)_5 = 34.67 \text{ gpm.}$$

iii) The general graphical design procedure for nonrectangular subunits is the same as for rectangular subunits. However, the F factors from table 7–6 must be adjusted and the x/L vs. scalar F′J ratios must be selected as outlined in the Manifold Design section of Design Procedures for Trickle Irrigation Systems.

iv) From figure 7–38 the shape adjustment factor for manifold (4) is $F_s = 0.88$; therefore, the adjusted pipe-friction reduction coefficient is

$$F' = 0.88 \times 0.38 = 0.34.$$

A summary of the graphical design results for manifold (4) is:

Pipe size (in.)	Length (ft)	Weight (lb)
2	236	99
2½	76	47
3	226	168
4	99.5	98
Totals	637.5	412

and $\triangle H_m = H_f = 6.3$ ft.

If the pipe sizes and lengths used for manifolds (1), (2), and (3) are also used for manifold (4), the approximate $\triangle H_m$ can be computed by equation 7–89 as

$$(H_f)_2 = \frac{637.5}{637.5}\left(\frac{0.88}{1.0}\right)\left[\frac{144}{178}\right]^{1.8} \times 6.3$$
$$(H_f)_2 = 3.8 \text{ ft} \cong (H_f)_4 = (\triangle H_m)_4.$$

This leaves 2.5 ft of extra pressure head, which cannot be used beneficially, that requires about 62 lb more pipe. The simplification of construction, however, that results from having manifolds (1) through (4) all the same, plus the savings in design effort, should more than offset the material cost difference.

v) For manifold (5), which serves a triangular subunit ($F_s = 1.54$ and $F' = 0.59$), an analysis by the graphical method for manifold (5) yields:

Pipe size (in.)	Length (ft)	Weight (lb)
1¼	100	21
1½	80	22
2	377	158
2½	80.5	50
Totals	637.5	251

and $\triangle H_m = H_f = 6.3$ ft.
For simplicity of design and better flushing capability, manifold (5) could be constructed of all 2-in.-diameter pipe. This would give

$$(\triangle H_m)_5 = 0.59 \times 1.54 \times 6.375 \qquad \textbf{(7–84)}$$
$$(\triangle H_m)_5 = 5.79 \text{ ft.}$$

The weight with all 2-in. pipe is 268 lb. The slightly higher cost of materials would be more than offset by eliminating the two sizes of pipe (1¼- and 1½-in.) from the project.

Simplifying the bill of materials, field layout, and installation by minimizing the number of pipe sizes used is important. The cost savings afforded by doing this are significant. Therefore, the recommended final design is:

Manifolds (1) through (4) use 150 ft of 2-in. pipe, 275 ft of 3-in. pipe, and 212.5 ft of 4-in. pipe as shown in part (v) of the section on the economic-chart method.

Manifold (5) uses all 2-in. pipe. This will require only:

Manifold number	Extra pipe (lb)
(1)	2
(2)	2
(3)	2
(4)	64
(5)	17
Total	87

This extra pipe will cost $87, based on $1.00/lb.

Manifold inlet pressure (H_m).—$h_l = 63.6$ ft, $(\triangle H_m)_1 = 6.4$ ft (3 pipe sizes), $(\triangle H'_m)_1 = 0.5(6.4) = 3.2$ ft; $(\triangle H_m)_5 = 5.8$ ft (all 2-in.), $(\triangle H'_m)_5 = 0.75(5.8) = 4.4$ ft.

i) For manifolds (1), (2), and (3),

$$H_m = 63.6 + 3.2 = 66.8 \text{ ft.} \qquad \textbf{(7–76a)}$$

ii) For manifold (5),

$$H_m = 63.6 + 4.4 = 68.0 \text{ ft.}$$

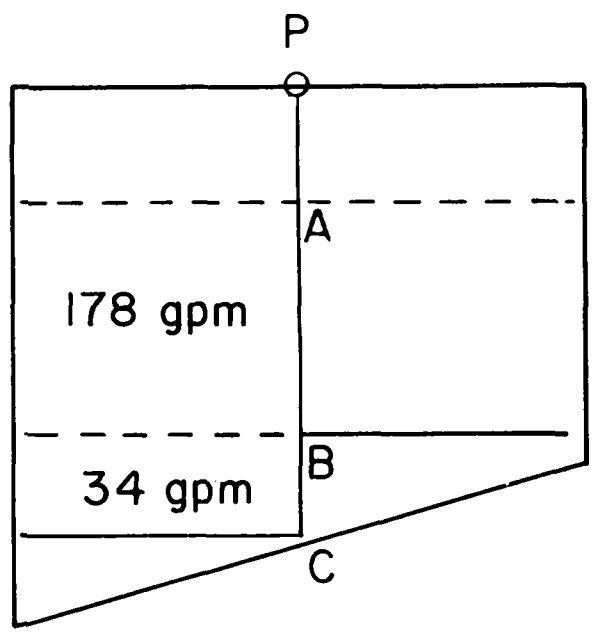
Main-Line Design

Selecting pipe sizes for main lines is based on economic, pressure, and velocity criteria. A detailed example of the use of the economic-chart method of main-line design was presented under Drip System. Therefore, only a summary of the design procedure will be presented here.

Economic pipe-size selection.

i) The highest main-line friction loss will occur at Station IV when manifolds (4) and (5) are in operation. (This is obvious, because all stations have the same flow rate, and the field is nearly level.)

When Station IV is operating, the flow is:



ii) Compute the h_f for each main-line pipe section. Use the economic pipe-size selection chart, figure 7–33, and equation 7–52 with J values from Appendix B. (The value of $Q'_s = 46$ gpm was computed for the manifold design in the section on the economic-chart method for rectangular subunits part [ii].)

Section	Flow (gpm)	Pipe (in.)	J	$\frac{L}{100}$	h_f (ft)
P–A	178	4	1.17[1]	2.70	3.16
A–B	178	4	1.17[1]	5.40	6.32
B–C	34	2	1.54	2.70	4.16

[1]Pipe selection controlled by 5 ft/s velocity restriction.

iii) The pressure head required to overcome pipe friction and elevation differences with $\triangle El = 0$ $[(H_{fe})_m]$ between the pump and each manifold is:

Point	Section From–to	Inlet (ft)	+	h_f (ft)	=	Point $(H_{fe})_m$ (ft)
A	P–A	0		8.0		8.0
B	A–B	8.0		6.3		14.3
C	B–C	14.3		2.7		17.0

Total Dynamic Head

The total dynamic head (TDH) required of the pump is the sum of the following pressure-head requirements:

	Item	ft[1]
(1)	Manifold (5) inlet pressure head	68.0
(2)	Pressure head to overcome pipe friction and elevation along the main line	17.0
(3)	Suction line, friction and lift	10.0
(4)	Filter—maximum pressure differential	23.1
(5)	Valve and fitting friction losses:	
	Fertilizer injection	—
	Flowmeter	3.0
	Main-line control valve	—
	Manifold inlet valve and pressure regulator	7.5
	Lateral risers and hose bibs	2.3
	Safety screens at manifold or lateral inlets	2.3
	Lateral or header pressure regulators	—
(6)	Friction loss safety factor at 10 percent	6.8
(7)	Additional pressure head to allow for emitter deterioration	—
Total		140.0

[1]See Drip System for comments.

System Design Summary

The final design layout is shown in figure 7–49. The design data are presented in figures 7–48 and 7–50. These three figures, along with a brief write-up of system specifications and a bill of materials, form the complete design package.

For irrigation scheduling the emission uniformity, net system application rate, and peak daily net system application should be:

Final emission uniformity (EU).—$H_m = 66.8$, $\triangle H_m = 6.4$, $\triangle h = 6.5$, $h_a = 58.7$, $x = 0.556$; for manifolds (1), (2), and (3), $v = 0.042$, $e = 1$.

i) Compute the ratio of the minimum emitter discharge to average emitter discharge by equations 7–38 and 7–39:

$$q_n/q_a = [\frac{66.8 - 6.4 - 6.5}{58.7}]^{0.556}$$

$$q_n/q_a = 0.95.$$

ii) If all manifolds are adjusted to have the same inlet pressure,

$$EU = 100[1 - (\frac{1.27}{\sqrt{1}} \times 0.042)]0.95 \qquad \textbf{(7–33a)}$$

$$EU = 90\%.$$

Net application rates (F_n and F_{mn}).—$S_p = 15$ ft, $S_r = 25$ ft, $e = 1$, $q_a = 11.43$ gph.

$$\text{i)}\ F_n = 1.604(\frac{90 \times 1 \times 11.43}{100 \times 15 \times 25}) \qquad \textbf{(7–40)}$$

$$F_n = 0.044 \text{ in./hr}$$

ii) After a system breakdown, each of the four stations can be operated 6 hr/day to give

$$F_{mn} = 0.044 \times 6$$

$$F_{mn} = 0.26 \text{ in./day.}$$

Line-Source System

The following line-source system design is for a typical field of staked tomatoes in Texas. The data that should be collected before beginning a design are summarized in the trickle irrigation design sheet, figure 7–53, and the field layout map, figure 7–54.

In addition to illustrating the general process of line-source irrigation design, the example emphasizes the following procedures:

1. Calculation of emission uniformity for line-source tubing.
2. Graphical design of downhill manifold so that friction slope closely follows ground slope.

The design computations that follow are made as brief as possible except for concepts that have not already been dealt with under Drip System and Spray System.

I	Project Name--Texas Line-Source Design	Date-Spring 1978
II	Land and Water Resources	
	a) Field no.	#1
	b) Field area (acres), A	4.70
	c) Average annual effective rainfall (in.), R_e	1.0
	d) Residual stored soil moisture from off-season precipitation (in.), W_s	0
	e) Water supply (gpm)	200+
	f) Water storage (acre-ft)	---
	g) Water quality (mmhos/cm), EC_w	1.0
	h) Water quality classification	Good
III	Soil and Crop	
	a) Soil texture	Clay loam
	b) Available water-holding capacity (in./ft), WHC	2.1
	c) Soil depth (ft)	6+
	d) Soil limitations	None
	e) Management-allowed deficiency (%), M_{ad}	30
	f) Crop	Tomato
	g) Plant spacing (ft x ft), S_p x S_r	3 x 5
	h) Plant root depth (ft), RZD	2.5
	i) Percent area shaded (%), P_s	50
	j) Average daily consumptive-use rate for the month of greatest overall water use (in./day), u_d	0.35
	k) Seasonal total crop consumptive-use rate (in.), U	25
	l) Leaching requirement (ratio), LR_t	0.04
IV	Emitter	
	a) Type	Mono-wall tubing
	b) Outlets per emitter	1
	c) Pressure head (psi), h	4.0
	d) Rated discharge @ h (gpm), q	0.0065
	e) Discharge exponent, x	0.48
	f) Coefficient of variability, v	0.12
	g) Discharge coefficient, k_d	0.00332
	h) Connection loss equivalent (ft), f_e	N/A

Figure 7-53.—Line-source-system data for Texas tomato field.

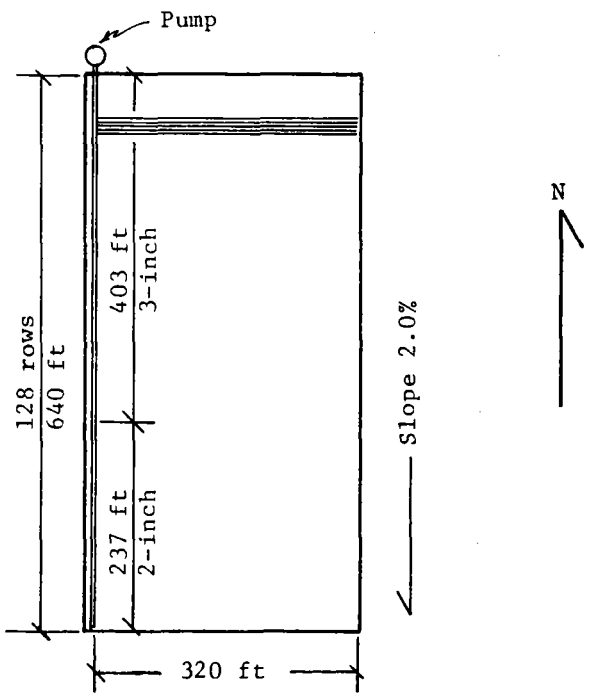


Figure 7–54.—Tomato field with line-source drip irrigation. Lateral lines are single-chamber 0.625-in. (ID) polyethylene tubing that discharge 0.4333 gpm/100 ft; the manifold is buried polyvinyl chloride pipe.

Design Factors

For a small field with a large water supply, it is really not necessary to compute all of the design factor details in figure 7–55, because the entire system can be operated simultaneously, and the irrigation only takes about 3 hr/day. Thus, irrigation could be achieved with a water supply one-sixth as large as that available, or six times as much land could be irrigated with the same water supply. If the water supply were much smaller or the area irrigated significantly larger, the design factor details would be needed. Therefore, figure 7–55 has been filled out, and a brief summary of the computations is included.

Computations for design.

i) From table 7–2 (fine-stratified) for equation 7–1,

$$P_w = \frac{2 \times 1.5 \times 5}{3 \times 5} \times 100$$
$$P_w = 100\%.$$

ii) $$F_{mn} = \frac{30}{100} \times 2.1 \times 2.5 \times \frac{100}{100} \qquad \textbf{(7–4)}$$
$$F_{mn} = 1.6 \text{ in.}$$

iii) $$T_d = 0.35[\frac{50}{100} + 0.15(1.0 - \frac{50}{100})] \qquad \textbf{(7–5)}$$
$$T_d = 0.20 \text{ in./day}$$

iv) From table 7–4,

max EC_e = 12.5 mmhos,

and

$$LR_t = \frac{1.0}{2(12.5)} = 0.04. \qquad \textbf{(7–17)}$$

v) T_r = 1.00; assumed EU = 80%

$$F_g = \frac{0.20 \times 1.00}{80/100} = 0.25 \text{ in.} \qquad \textbf{(7–8a)}$$

vi) $$F_{(gp/d)} = \frac{0.623 \times 0.25 \times 3.0 \times 5.0}{1.0} \qquad \textbf{(7–9)}$$
$$F_{(gp/d)} = 2.34 \text{ gal/day.}$$

vii) $$T_a = \frac{2.34}{2 \times 0.39} = 3.00 \text{ hr/day} \qquad \textbf{(7–30)}$$

viii) Lines a), b), c), d), e), g), and h) in the Final Design, Part II of figure 7–55, are repeats of the data already computed, because no adjustments in the application time were called for.

ix) Although there is only one orifice per plant, the water spread is more than 4 ft, so that each tomato plant will have access to water from at least three outlets. Thus, e′ = 3 in equation 7–33a, and

$$q_n = \frac{0.0065 \times 80/100}{1.0 - 0.12 \times 1.27/\sqrt{3}}$$
$$q_n = 0.0057 \text{ gpm.}$$

$$h_n = 4.0(\frac{0.0057}{0.0065})^{1/0.48} = 3.04 \text{ psi} \qquad \textbf{(7–31)}$$

$$\triangle H_s = 2.5(4.0 - 3.04) \qquad \textbf{(7–34)}$$
$$\triangle H_s = 2.4 \text{ psi or } 5.54 \text{ ft.}$$

x) $$Q_s = 726 \times \frac{4.70}{1} \times \frac{0.39}{1.5 \times 5.0} \qquad \textbf{(7–35b)}$$
$$Q_s = 177 \text{ gpm.}$$

I	Project Name--Texas Line-Source Design	Date-Spring 1978
II	Trial Design	
a)	Emission point layout	Line-source
b)	Emitter spacing (ft x ft), $S_e \times S_l$	1.5 x 5.0
c)	Emission points per plant, e	2
d)	Percent area wetted (%), P_w	100
e)	Maximum net depth of application (in.), F_{mn}	1.6
f)	Ave. peak transpiration rate (in./day), T_d	0.20
g)	Maximum allowable irrigation interval (days), I_f	8
h)	Design irrigation interval (days), I_f	1
i)	Net depth of application (in.), F_n	0.20
j)	Emission uniformity (%), EU	80
k)	Gross water application (in.), F_g	0.25
l)	Gross volume of water required per plant per day (gal/day), $F_{(gp/d)}$	1.17
m)	Time of application (hr/day), T_a	3.00
III	Final Design	
a)	Time of application (hr/day), T_a	3.00
b)	Design irrigation interval (days), I_f	1
c)	Gross water application (in.), F_g	0.25
d)	Average emitter discharge (gph), q_a	0.39
e)	Average emitter head (ft), h_a	9.24
f)	Allowable pressure-head variation (ft), ΔH_s	5.54
g)	Emitter spacing (ft x ft), $S_e \times S_l$	1.5 x 5.0
h)	Percent area wetted (%), P_w	100
i)	Number of stations, N	1
j)	Total system capacity (gpm), Q_s	177
k)	Seasonal irrigation efficiency (%), E_s	80
l)	Gross seasonal volume (acre-ft), V_i	7.0
m)	Seasonal operating time (hr), Q_t	215
n)	Total dynamic head (ft), TDH	131
o)	Actual uniformity (%), EU	86
p)	Net water-application rate (in./hr), F_n	0.0717

Figure 7–55.—Line-source-system design factors for Texas tomato field.

xi) From table 7–3 (fine, 2.5 ft),

$$T_R < 1/(1.0 - LR_t),$$

and with excellent scheduling,

$$E_s = EU = 80\% \qquad \textbf{(7–11)}$$

xii) $$F_{(an)} = (25 - 1)[\frac{50}{100} + 0.075] \qquad \textbf{(7–10)}$$

$$F_{(an)} = 13.8 \text{ in.}$$

$$V_i = \frac{13.8 \times 4.70}{12(1 - 0.04)(80/100)} \qquad \textbf{(7–14)}$$

$$V_i = 7.0 \text{ acre-ft.}$$

$$Q_t = \frac{5{,}430 \times 7.0}{177} \qquad \textbf{(7–37)}$$

$$Q_t = 215 \text{ hr/year}$$

Lateral Line Design and System Layout

Lateral-line design procedures are essentially the same for all trickle irrigation systems. The procedure includes determining the manifold spacing, the manifold layout, the lateral size (or sizes in the case of tapered laterals), and the maximum variation of pressure head along the laterals.

Single-chamber tubing was recommended for this design because it can be flushed. Clogging problems were anticipated because the irrigation water contains 3 ppm of iron, even though chlorination was used.

Because the water supply is large, it was decided that to simplify operation and maintenance only one operating station would be used. Furthermore, the farmer wanted the tomato rows to run east-west and the manifold to be buried along the west side of the field. This established the system layout (the manifold spacing and layout), as shown in figure 7–54.

Lateral-pipe size selection and head variation ($\triangle h$).—$q_a = 0.39$ gph, $S_e = 1.5$ ft, $l = 319.5$ ft; from table 7–6, $F = 0.36$; $\triangle H_s = 5.54$ ft.

i) The lateral flow rate is:

$$q_l = \frac{319.5}{1.5} \times \frac{0.39}{60} \qquad \textbf{(7–62)}$$

$$q_l = 1.38 \text{ gpm.}$$

ii) Both 0.625-in. and 0.824-in. ID single-chamber tubing are available. Trying the 0.625-in. tubing first, compute the J value by equation 7–49a (because there is not a table for 0.625-in. ID tubing in Appendix B):

$$J = 0.133 \times \frac{(1.38)^{1.75}}{(0.625)^{4.75}}$$

$$J = 2.18.$$

iii) Because the laterals are laid on the contour, $\triangle h = h_f$ and

$$\triangle h = 2.18 \times 0.36 \times \frac{319.5}{100}$$

$$\triangle h = 2.51 \text{ ft.}$$

iv) The 0.625-in. tubing should be satisfactory because

$$\triangle h < 0.5\triangle H_s = 2.77 \text{ ft,}$$

which leaves

$$(\triangle H_m)_a = 3.03 \text{ ft.}$$

Lateral inlet pressure head (h_l).—$h_a = 9.24$ ft, $h_f = 2.51$ ft, $\triangle El = 0$.

For a single lateral with a constant diameter on a level field,

$$h_l = 9.24 + 3/4(2.51) = 11.1 \text{ ft.} \qquad \textbf{(7–63c)}$$

Manifold Design

Three possible manifold configurations that will stay within the small allowable $(\triangle H_m)_a = 3.03$ ft on the relatively steep 2-percent slope are:

1. A tapered manifold carefully selected so that the friction slope closely follows the ground slope.
2. Headers and pressure (or flow) regulators used as shown in figure 7–5.
3. Flow regulators or jumper tubes of various lengths used to compensate for excessive pressure variations.

It was decided that a carefully tapered manifold would be ideal for meeting the farm's long-term requirements, provided that the desired design precision could be achieved, i.e., an EU of at least 80 percent. A tapered manifold system should be cheaper, simpler, and more durable than a system requiring flow or pressure regulators.

The graphical methods of designing manifolds are better than the economic-chart method for design-

ing downhill lines with a small $(\triangle H_m)_a$. With the graphical methods the $\triangle H_m$ can be accurately controlled; this control is difficult with the economic method. Inasmuch as the field is rectangular, the alternative graphical method was used because it is much faster than the general graphical method.

Alternative graphical method.—S_l = 5.0 ft, q_l = 1.38 gpm; $(\triangle H_m)_a$ = 3.03 ft; S = 2%. To determine the lengths of different-diameter pipes from figure 7–34: for 1.5-in., (27.4/177) × 640 = 99 ft; for 2-in., 48.7 − 27.4 = 21.3 and (21.3/177) × 640 = 77 ft. k = 0.36; weight of original solution = 385 lb.

i) Because q_l = 1.38 gpm, the standard manifold curves presented in figure 7–36 were used.

By equation 7–79a,

$$k = \left(\frac{5.0}{1.38}\right)(0.1)$$
$$k = 0.36.$$

ii) Because the manifold serves 128 rows, the flow rate is

$$q_m = 128 \times 1.38 = 177 \text{ gpm},$$

and the length of the manifold is

$$L_m = 128 \times 5.0 = 640 \text{ ft}$$

because the length to the first outlet was a full (rather than a half) row spacing.

iii) In accordance with the instructions in step 5′ in the Alternative Graphical Design Method under Manifold Design, which are discussed under Spray System, determine j′ by equation 7–87:

$$j' = \frac{3.03}{0.36} = 8.4 \text{ ft};$$

and S′ by equation 7–88:

$$S' = \frac{2 \times 177}{10} = 35.4 \text{ ft}.$$

iv) Following steps 6′, 7b′, and 8′ in the Alternative Graphical Design Method, construct figure 7–41. Step 7b′ was used because S′ > 3j′, i.e., 35.4 > 3(8.4). The solid sloping line from the origin to S′ = 35.4 ft at q_m = 177 gpm represents the ground slope drawn to the same scale as the standard manifold friction curves in figure 7–36. The sloping dashed line which is j′ = 8.4 ft above the slope line represents the upper limit of pressure variation. Any combination of lengths of pipe of different diameters that will satisfy the design requirements will have a composite friction curve defined by the two sloping lines. The procedure for drawing the least-cost composite curve is given in step 8′.

v) One design possibility, involving four pipe sizes, is:

Pipe size (in.)	Length (ft)	Weight (lb)
1½	99	27
2	77	32
2½	144	89
3	320	237
Total	640	385

This design produces a pressure head variation of

$$\triangle H_m = 0.36 \times 6.1$$
$$\triangle H_m = 2.2 \text{ ft}.$$

A simple manifold configuration would be a combination of 2- and 3-in. pipe, as indicated by the dashed curve extensions on figure 7–41. A summary of the two-pipe-size design is:

Pipe size (in.)	Length (ft)	Weight (lb)
2	237	99
3	403	299
Total	640	398

The two-pipe design would have the same pressure-head variation ($\triangle H_m$ = 2.2 ft) as the original design, but would require 13 lb more pipe. The savings in layout and installation costs afforded by eliminating two sizes of pipes would probably more than offset the extra cost for pipe.

Manifold inlet pressure (H_m).—k = 0.36; h_l = 11.1 ft.

i) The amount the manifold inlet pressure differs from h_l ($\triangle H'_m$) can be estimated graphically as demonstrated on figure 7–41 for the 2- and 3-in. pipe-size design. The thin line parallel to and above the ground-slope line is the average lateral emitter pressure line. It is positioned so that the cross-hatched areas (defined by it and the 2- and 3-in. pipe-friction curves) above and below it are about equal. The manifold inlet pressure is 4.6 graph units above it, therefore

$\triangle H'_m = 0.36 \times 4.6$
$\triangle H'_m = 1.7$ ft,

and by equation 7–76a,

$H_m = 1.11 + 1.7 = 12.8$ ft.

Main-Line Design

For the tomato field layout (fig. 7–54) there are only a few feet of main line and this should be 3-in. pipe.

Total Dynamic Head

The total dynamic head (TDH) required is the sum of the following pressure head requirements:

Item		ft[1]
(1)	Manifold inlet pressure	12.8
(2)	Main line	—
(3)	Dynamic lift from well	78.0
(4)	Filter—maximum pressure differential	23.1
(5)	Valve and fitting losses	9.2
(6)	Friction-loss safety factor	3.7
(7)	Additional pressure head to allow for emitter deterioration	4.6
Total		131.4

[1]See Drip System for comments.

System Design Summary

The final design layout is shown in figure 7–54. The design data are presented in figures 7–53 and 7–55. These three figures, along with a brief writeup of system specifications and a bill of materials, form the complete design package.

For irrigation scheduling the emission uniformity, net system application rate, and peak daily net application should be:

Final emission uniformity (EU).—$H_m = 12.8$ ft, $\triangle H_m = 2.2$ ft, $\triangle h = 2.51$ ft, $x = 0.48$; $h_a = 9.24$ ft; $v = 0.12$; use $e' = 2$ because of over-lapping spread of water.

i) compute q_n/q_a by equations 7–38 and 7–39:

$$\frac{q_n}{q_a} = \left[\frac{12.8 - 2.2 - 2.5}{9.2}\right]^{0.48}$$

$$\frac{q_n}{q_a} = 0.94.$$

ii) Compute EU by equation 7–33a:

$$EU = 100 \times [1 - \frac{1.27}{\sqrt{3}} \times 0.12] \times 0.94$$

$$EU = 86\%.$$

Net application rates (F_n and F_{mn}).—$S_p = 3$ ft, $S_r = 5$ ft, $e = 2$, $q_a = 0.39$ gph, EU = 86%.

i) By equation 7–40,

$$F_n = 1.604 \times \frac{86}{100} \times \frac{2 \times 0.39}{3 \times 5}$$

$$F_n = 0.0717 \text{ in/hr.}$$

ii) In a 24-hr period the system could apply

$$F_{mn} = 24 \times 0.0717 = 1.72 \text{ in/day.}$$

This is far higher than necessary for meeting contingencies, and the system can be expanded to cover more than six times as much land with the same water supply.

Field Evaluation

Successful trickle irrigation requires that the frequency and quantity of water application be scheduled accurately. Uniformity of field emission (EU') must be known to manage the quantity of application. Unfortunately, EU' often changes with time; therefore, the system's performance must be checked periodically.

The data needed for fully evaluating a trickle irrigation system are:

1. Duration, frequency, and operation sequence of a normal irrigation cycle.
2. Soil moisture deficit (S_{md}) and management-allowed deficit (M_{ad}) in the wetted volume.
3. Rate of discharge at the emission points and pressure near several emitters spaced throughout the system.
4. Changes in rate of discharge from emitters after cleaning or other repair.
5. Percentage of soil volume wetted.
6. Spacing and size of trees or other plants being irrigated.
7. Location of emission points relative to trees, vines, or other plants, and uniformity of emission point spacing.
8. Losses of pressure at the filters.
9. General topography.
10. Additional data indicated on figure 7–56.

Equipment Needed

The equipment needed for collecting the necessary field data includes:

1. Pressure gage (0- to 5-psi range) with "T" adapters for temporary installation at either end of the lateral hoses.
2. Stopwatch or watch with an easily visible second hand.
3. Graduated cylinder with 250-ml capacity.
4. Measuring tape 10 to 20 ft long.
5. Funnel with 3- to 6-in. diameter.
6. Shovel and soil auger or probe.
7. Manufacturer's emitter performance charts showing the relation between discharge and pressure, plus recommended operating pressures and filter requirements.
8. Sheet metal or plastic trough 3 ft long for measuring the discharge from several outlets in a perforated hose simultaneously or the discharge from a 3-ft length of porous tubing. (A piece of 1- or 2-in. PVC pipe cut in half lengthwise makes a good trough.)
9. Copies of figure 7–56 for recording data.

Field Procedure

The following field procedure is suitable for evaluating systems that have individually manufactured emitters (or sprayers) and systems that use perforated or porous lateral hose. Fill in the blanks of figure 7–56 while conducting the field procedure.

1. Fill in parts 1, 2, and 3 concerning the general soil and crop characteristics throughout the field.
2. Determine from the operator the duration and frequency of irrigation and his estimate of the management-allowed deficit (M_{ad}) to complete part 4.
3. Check and note in part 5 the pressures at the inlet and outlet of the filter, and if practical, inspect the screens for breaks and the screen fittings for passages allowing contaminants to bypass the screens.
4. Fill in parts 6, 7, and 8, which deal with the emitter and lateral hose characteristics. (When perforated or porous tubing is tested, the discharge may be rated by the manufacturer in flow per unit length.)
5. Locate four emitter laterals along an operating manifold (see figure 7–27); one should be near the inlet, two near the one-third points, and the fourth near the outer end. Sketch the system layout and note in part 9 the general topography, manifold in operation, and manifold where the discharge test will be conducted.
6. Record the system discharge rate (if the system is provided with a water meter) and the numbers of manifolds and blocks or stations. The number of blocks is the total number of manifolds divided by the number of manifolds in operation at any one time.
7. For laterals having individual emitters, measure the discharge at two adjacent emission points (denote as A and B in part 14) at each of four tree or plant locations on each of the four selected test laterals. (See figure 7–57.) Collect the flow for a few minutes to obtain a volume between 100 and 250 ml for each emission point tested. Convert each reading to milliliters per minute before entering the data in part 14. To convert milliliters per minute to gallons per hour, divide by 63.

These steps will produce eight pressure readings and 32 discharge volumes at 16 plant locations for individual emission points used in wide-spaced crops that have two or more points per plant.

For perforated hose or porous tubing, use the 3-ft trough and collect a discharge reading at each of the 16 locations described above. Because these are already averages from two or more outlets, only one reading is needed at each location.

For relatively wide-spaced crops such as grapes, where one single outlet emitter may serve one or more plants, collect a discharge reading at each of the 16 locations described above. Because the plants are served by only a single emission point, only one reading should be made at each location.

8. Measure and record in part 15 the water pressures at the inlet and downstream ends of each lateral tested in part 14 under normal operation. On the inlet end this requires disconnecting the hose before reading the pressure. On the downstream end the pressure can be read after connecting the pressure gage in the simplest way possible.

9. Check the percentage of the soil that is wetted at one of the tree locations on each test lateral and record it in part 16. It is best to select a tree at a different relative location on each lateral. Use the probe, soil auger, or shovel—whichever seems to work best—for estimating the real extent of the wetted zone about 6 to 12 in. below the surface around each tree. Determine the percent area wetted by dividing the wetted area by the total surface area between four trees.

10. If an interval of several days between irrigations is being used, check the soil moisture deficit (S_{md}) in the wetted volume near a few representative trees in the next block to be irrigated, and record it in part 17. This measurement is difficult and requires averaging samples taken from several positions around each tree.

11. Determine the minimum lateral inlet pressure (MLIP) along each operating manifold and record it in part 18. For level or uphill manifolds, the MLIP will be at the far end of the manifold. For downhill manifolds it is often about two-thirds down the manifold. For manifolds on undulating terrain it is usually on a knoll or high point. When evaluating a system that has two or more operating stations, the MLIP on each manifold should be determined. This requires cycling the system.

12. Determine the discharge correction factor (DCF) to adjust the average emission-point discharges for the tested manifold. This adjustment is needed if the tested manifold happened to be operating with a higher or lower MLIP than the system average MLIP. If the emitter discharge exponent (x) is known, use the second formula printed in part 19.

13. Determine the average and adjusted average emission-point discharges according to the equations in part 11 and 12.

Using Field Data

In trickle irrigation all the system flow is delivered to individual trees, vines, shrubs, or other plants. Essentially no water is lost except at the tree or plant locations. Therefore, if the pattern of plant distribution or spacing is uniform, uniformity of emission is of primary concern. Locations of individual emission points, or the tree locations where several emitters are closely spaced, can be thought of in much the same manner as the container positions in tests of sprinkler performance.

Average Depth of Application

The average depth applied per irrigation to the wetted area (F'_{aw}), inches, is useful for estimating M_{ad}. It can be computed by equation 7–90.

$$F'_{aw} = \frac{1.604 e q'_a T_a}{A_w} \qquad \textbf{(7–90)}$$

Where

e = number of emission points per tree.
q'_a = adjusted average emission-point discharge of the system, taken from part 12, figure 7–56, gallons per hour.
T_a = application time per irrigation, hours.
A_w = area wetted per tree or plant from part 16, figure 7–56, square feet.

The average depth applied per irrigation to the total cropped area (F'_a), inches, can be found by substituting the plant and row spacing ($S_p \times S_r$) for A_w in equation 7–90. Therefore, F'_a can be computed by equation 7–91.

$$F'_a = \frac{1.604 e q'_a T_a}{S_p \times S_r} \qquad \textbf{(7–91)}$$

1. Location _____, observer _____, date _____

2. Crop: type _____, age _____ years, spacing _____ ft

   root depth _____ ft, percentage of area covered or shaded ____ %

3. Soil: texture _____, available moisture _____ in/ft

4. Irrig: duration ____ hr, frequency ____ days, M_{ad} ____ %, _____ in

5. Filter pressure: inlet ____ psi, outlet ____ psi, loss _____ psi

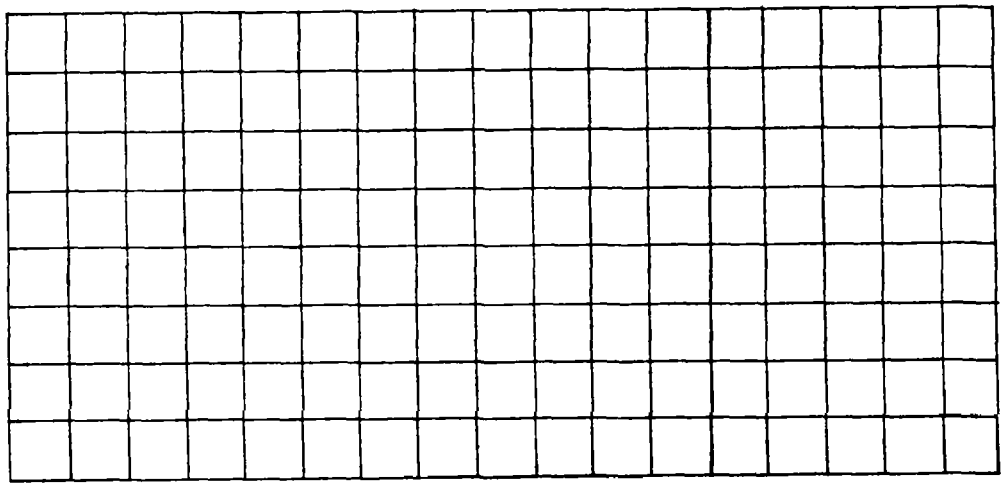
6. Emitter: make _____, type _____, point spacing ____ ft

7. Rated discharge per emission point _____ gph at _____ psi

   Emission points per plant _____, giving _____ gal. per plant per day

8. Hose: diameter ____ in, material _____, length ____ ft, spacing ____ ft

9. System layout, general topography, and test locations:



10. System discharge ____ gpm, no. of manifolds _____ and blocks _____

11. Average test manifold emission-point discharges at _____ psi

$$\text{Manifold} = \frac{(\text{sum of all averages} \qquad \text{gph})}{(\text{number of averages} \qquad)} = \underline{\qquad\qquad} \text{ gph}$$

$$\text{Low } 1/4 = \frac{(\text{sum of low } 1/4 \text{ averages} \qquad \text{gph})}{(\text{number of low } 1/4 \text{ averages} \qquad)} = \underline{\qquad\qquad} \text{ gph}$$

Figure 7-56.—Form for evaluation data.

12. Adjusted average emission-point discharges at _____ psi

System = (DCF[1/] _____) X (manifold average _____ gph) = _____ gph

Low 1/4 = (DCF _____) X (manifold low 1/4 _____ gph) = _____ gph

13. Comments: _____

_____

_____

_____

14. Discharge test volume collected in _____ min (1.0 gph = 63 ml/min)

Outlet location on lateral		Lateral location on the manifold							
		inlet end		1/3 down		2/3 down		far end	
		ml	gph	ml	gph	ml	gph	ml	gph
inlet end	A								
	B								
	Ave.								
1/3 down	A								
	B								
	Ave.								
2/3 down	A								
	B								
	Ave.								
far end	A								
	B								
	Ave.								

1/See item 19.

Figure 7-56.—Form for evaluation data (continued).

15. Lateral inlet _____ psi _____ psi _____ psi _____ psi

Closed end _____ psi _____ psi _____ psi _____ psi

16. Wetted area _____ ft^2 _____ ft^2 _____ ft^2 _____ ft^2

per plant _____ % _____ % _____ % _____ %

17. Estimated average S_{md} in wetted soil volume _____ in

18. Minimum lateral inlet pressure (MLIP) on all operating manifolds:

Manifold:	Test	A	B	C	D	E	F	G	Ave.
Pressure-psi:	____	____	____	____	____	____	____	____	____

19. Discharge correction factor (DCF) for the system is:

$$DCF = \frac{2.5 \text{ X (average MLIP \_\_\_\_\_ psi)}}{\text{average MLIP \_\_\_\_\_ psi + 1.5 X (test MLIP \_\_\_\_\_ psi)}} = \_\_\_\_\_$$

or if the emitter discharge exponent x = _____ is known,

$$DCF = \left[\frac{\text{(average MLIP \_\_\_\_\_ psi)}}{\text{(test MLIP \_\_\_\_\_ psi)}}\right]^x = \_\_\_\_\_ = \_\_\_\_\_$$

Figure 7-56.—Form for evaluation data (continued).

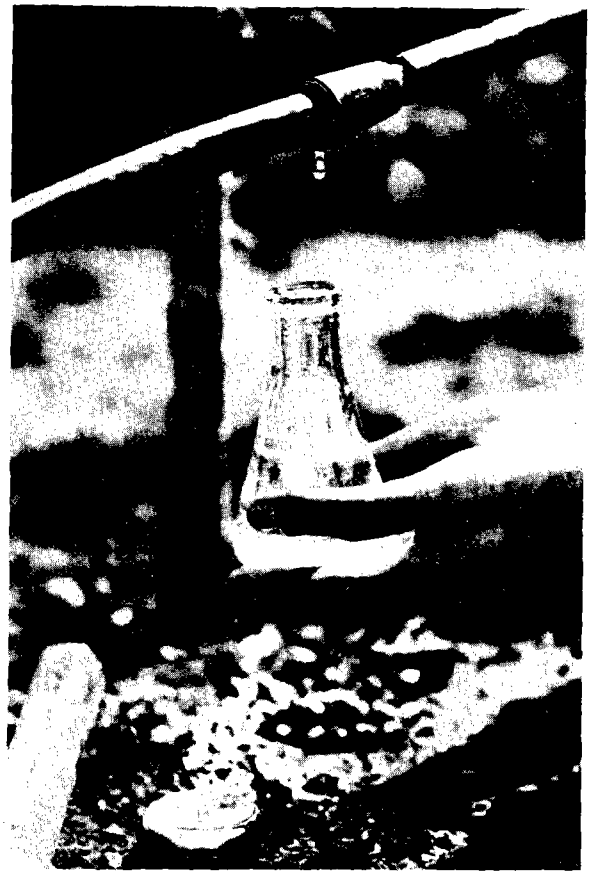


Figure 7–57.—Field measurement of discharge from an emitter.

Volume Per Day

The average volume of water applied per day for each tree or plant [$F'_{(gp/d)}$], gallons per day, can be computed by equation 7–92.

$$F'_{(gp/d)} = \frac{eq_a'T_a}{I_f} \qquad \textbf{(7–92)}$$

Where

e = number of emission points per tree.
q_a' = adjusted average emission-point discharge of the system, taken from part 12, figure 7–56, gallons per hour.
T_a = application time per irrigation, hours.
I_f = design irrigation interval, days.

Emission Uniformity

The actual field-emission uniformity (EU′) is needed to determine the system's operating efficiency and to estimate gross requirements for water application. The EU′ is a function of the emission uniformity in the tested area and of the pressure variations throughout the entire system. Where the data on emitter discharge are from an area served by a single manifold, the field emission uniformity of the manifold area tested (EU'_m), percent, can be computed by equation 7–93.

$$EU'_m = 100\, q_n'/q_a' \qquad \textbf{(7–93)}$$

Where

q_n' and q_a' = system low-quarter and overall average emitter discharges, taken from part 12, figure 7–56, gallons per hour.

Some trickle irrigation systems are fitted with pressure-compensating emitters or have pressure or flow regulation at the inlet to each lateral. However, most systems are provided with a means for pressure control or regulation only at the inlets to the manifolds. If the manifold inlet pressures vary more than a few percent because of design, management, or both, the overall EU′ will be lower than the EU'_m of the tested manifold.

An estimate of this efficiency reduction factor (ERF) can be computed from the minimum lateral inlet pressure along each manifold (MLIP), pounds per square inch, throughout the system by equations 7–94a and 7–94b.

$$ERF = \frac{\text{average MLIP} + (1.5 \text{ minimum MLIP})}{2.5(\text{average MLIP})} \qquad \textbf{(7–94a)}$$

Where

Average MLIP = average of the individual MLIP's along each manifold, pounds per square inch.
Minimum MLIP = lowest lateral inlet pressure in the system, pounds per square inch.

The ERF may be estimated more precisely by equation 7–94b.

$$ERF = \left(\frac{\text{minimum MLIP}}{\text{average MLIP}}\right)^x \qquad \textbf{(7–94b)}$$

In systems where the variations in pressure are relatively small and the emitter discharge exponent (x) ≅ 0.5, the two methods for computing ERF give essentially equal results; however, for variations in pressure greater than 0.2 times the average emitter pressure head (h_a) or x values higher than 0.6 or lower than 0.4, the differences may be significant.

The value of x can be estimated from field data as follows:

Step 1. Determine the average discharge and pressure of a group of at least six emitters along a lateral where the operating pressure is uniform.

Step 2. Reduce the operating pressure by adjusting the lateral inlet valve, and again determine the average discharge and pressure of the same group of emitters.

Step 3. Determine x by equation 7–21, using the average discharge and pressure-head values found in steps 1 and 2.

Step 4. Repeat steps 1, 2, and 3 at two other locations and average the x values for the three tests.

The ERF approximately equals the ratio between the average emission-point discharge in the area served by the manifold with the minimum MLIP and the average emission-point discharge for the system. Therefore, the system EU′ can be approximated by equation 7–95.

$$EU' = (ERF)(EU'_m) \qquad \textbf{(7–95)}$$

General criteria for EU′ values for systems that have been operated for one or more seasons are: greater than 90 percent, excellent; between 80 percent and 90 percent, good; 70 to 80 percent, fair; and less than 70 percent, poor.

Gross Application Required

Because trickle irrigation wets only a small portion of the soil volume, the soil moisture deficit (S_{md}) must be replaced frequently. It is always difficult to estimate S_{md} because some regions of the wetted part of the root zone often remain near field capacity even when the interval between irrigations is several days. For this reason, S_{md} must be estimated from weather data or from information obtained from evaporation devices. Such estimates are subject to error, and because there is no practical way to check for slight underirrigation, some margin for safety should be allowed. As a general rule, the minimum gross depth of application (F_g) should be equal to or slightly greater than the values obtained by equation 7–8a or 7–8b.

When estimating F_g by equation 7–8a or 7–8b for scheduling irrigations, let EU be the field value (EU′) and estimate the net depth of irrigation to apply (F_n) as follows:

1. Estimate the depth of water that could have been consumed by a full-canopy crop since the previous irrigation (F'_n), inches. This can be estimated by standard techniques based on weather data or pan evaporation data.
2. Subtract the depth of effective rainfall since the last irrigation (R'_e), inches.
3. Calculate F_n by equation 7–96.

$$F_n = (F'_n - R'_e)\left[\frac{P_s}{100} + 0.15\left(1.0 - \frac{P_s}{100}\right)\right] \qquad \textbf{(7–96)}$$

Where

P_s = percent shaded.

Using F_g computed by equation 7–8a or 7–8b, the average daily gross volume of water required per plant per day [$F_{(gp/d)}$] can be computed by equation 7–9.

The average volume of water actually being applied per plant each day [$F'_{(gp/d)}$] is computed by equation 7–92. If $F_{(gp/d)} < F'_{(gp/d)}$, the field is being overirrigated, and if $F_{(gp/d)} > F'_{(gp/d)}$, it is underirrigated.

Application Efficiencies

A concept called "potential application efficiency" (of the low quarter) (PE_{lq}) is useful for estimating how well a system can perform. It is a function of the peak-use transpiration ratio (T_r), the leaching requirement (LR_t), and the uniformity of field emission (EU′). When the unavoidable water losses are greater than the leaching water requirements, T_r >

$1/(1.0 - LR_t)$, PE_{lq} can be computed by equation 7–97a

$$PE_{lq} = \frac{EU'}{T_r(1.0 - LR_t)} \qquad \textbf{(7–97a)}$$

and when $T_r < 1/(1.0 - LR_t)$, PE_{lq} can be computed by equation 7–97b.

$$PE_{lq} = EU' \qquad \textbf{(7–97b)}$$

The values of T_r appear in conjunction with equation 7–8a, and those of LR_t, with equation 7–16.

A trickle irrigation system has no field boundary effects or pressure variations along the manifold tested that are not taken into account in the field estimate of EU′. Therefore, the PE_{lq} estimated with the system EU′ is an overall value for the field, except for possible minor water losses from leaks, draining of lines, and flushing (unless leaks are excessive) (see equation 7–95).

The system PE_{lq} may be low because the manifold inlet pressures are not properly set and ERF (see equations 7–94a and 7–94b) is low. In such a system the manifold inlet pressures should be adjusted to increase the uniformity of pressure and consequently ERF. When an area is overirrigated, the actual application efficiency of the low quarter (E_{lq}) is less than PE_{lq}. In such areas the E_{lq} can be estimated by equation 7–98.

$$E_{lq} = \frac{100G}{F'_{(gp/d)}} \qquad \textbf{(7–98)}$$

Where

G	=	gross water required per plant during the peak use period, gallons per day.
$F'_{(gp/d)}$	=	average volume of water applied per plant per day, gallons per day.

When an area is underirrigated and $F'_{(gp/d)}$ is less than the average daily gross volume of water required per plant per day [$F_{(gp/d)}$], then E_{lq} will approach the system EU′. In such areas the LR_t, the T_r, or both will not be satisfied. This may cause either excessive buildup of salt along the perimeters of wetted areas or a reduced volume of wetted soil.

Appendix A—Nomenclature

a = flow cross-section area (square inches)
A = field area under the system (acres)
A_f = system flow-rate adjustment factor
A_s = soil surface area directly wetted by the sprayer (square feet)
A_w = horizontal area wetted about 1 ft below soil surface (square feet)

BHP = brake horsepower

c = concentration of the desired component in liquid chemical concentrate (percent)
c = number of pipe sizes used in the manifold
C = desired dosage of chlorine or acid (parts per million)
C = friction coefficient for continuous section of pipe
C = cost of the irrigation system
c_q = coefficient that depends on the characteristics of the nozzle
c_t = required tank capacity (gallons)
C_{whp} = annual cost per water horsepower (dollars per water horsepower-season)
CRF = capital recovery factor

d = flow cross-section diameter (inches)
D = inside diameter of pipe (inches)
DCF = discharge correction factor

e = number of emission points or sprayers per plant
e' = minimum number of emitters or sprayers from which each plant can obtain water
E = present annual power cost
E' = equivalent annual cost of the rising (9 percent per year) energy cost
E_{lq} = actual application efficiency of the low quarter
E_p = pump efficiency
E_s = seasonal irrigation efficiency
EAE(r) = equivalent annualized factor of the rising energy cost at rate r
EC_{dw} = electrical conductivity of the drainage effluent (mmhos per centimeter)
EC_e = electrical conductivity of the saturated extract (mmhos per centimeter)
EC_w = electrical conductivity of the irrigation water (mmhos per centimeter)
$\triangle El$ = change in elevation; positive for laterals running uphill from the inlet and negative for downhill laterals (feet)
$\triangle El$ = difference in elevation between the pump and manifold; positive if uphill to manifold and negative if downhill (feet)
ERF = efficiency reduction factor
EU = design emission uniformity (percent)
EU' = uniformity of field emission (percent)
EU'_m = field emission uniformity of the manifold area tested (percent)

f = Darcy-Weisbach pipe-friction factor
F = reduction coefficient to compensate for the discharge along the pipe
F'_a = average depth applied per irrigation to the total cropped area (inches)
F_{an} = annual net depth of application (inches)
F'_{aw} = average depth applied per irrigation to the wetted area (inches)
F_c = concentration of nutrients in liquid fertilizer (pounds per gallon)
f_e = emitter-connection loss equivalent length (feet)
F_g = gross depth of application at each irrigation (inches)
$F_{(gal/d)}$ = gross volume of water required per day (gallons per day)
$F_{(gp/d)}$ = average volume of water applied per plant per day (gallons per day)
F_{mn} = maximum net depth of application (inches)
F_n = net application rate (inches per hour)
F_n = net depth of application (inches)
F'_n = depth of water consumed by full canopy crop since previous irrigation (inches)
F_r = rate of fertilizing (pounds per acre)
F_s = manifold pipe-friction adjustment factor
$(F_s)_1$ = friction adjustment factor for the original manifold
$(F_s)_2$ = friction adjustment factor for the manifold for which $(H_f)_2$ is being estimated
$F_{(sg)}$ = gross seasonal depth of application (inches)

g = acceleration of gravity (32.2 feet per second squared)
G = gross water required per plant during the peak use period (gallons per day)

h = working pressure head of inner main chamber (feet)
h = working pressure head at the emitter (pounds per square inch)
H = time of actual irrigating per irrigation cycle (hours)

$\triangle H$ = desired pressure-head increase between two points (feet)
$\triangle h$ = difference in pressure head along the laterals (feet)
$\triangle h'$ = amount the lateral inlet pressure differs from h_a (feet)
$(100\ \triangle h/L)'$ = maximum scalar distance between the friction curve and the ground surface line in the graphical solution
h_a = pressure head that will give the q_a (feet)
H_a = average manifold pressure
h_c = pressure head at the closed end of the lateral (feet)
$\triangle h_c$ = difference between the downstream-end and minimum pressure heads (feet)
h_e = friction head loss caused by a specific fitting (feet)
H_f = pressure-head loss in the manifold from pipe friction (feet)
h_f = lateral head loss from pipe friction (feet)
$\sum_1^m h_f$ = sum of the pipe-friction losses between the pump and manifold inlet at m (feet)
$(h_f)_a$ = original lateral pipe-friction loss (feet)
$(h_f)_b$ = new lateral pipe-friction loss (feet)
$h_{f(a,b)}$ = difference in head loss between adjacent pipes of different sizes (feet)
$(H_{fe})_m$ = pressure head to overcome pipe friction and elevation along the main line (feet)
$(h_f)_m$ = friction loss along the manifold (feet)
h_{fp} = friction loss in a lateral with length (L) (feet)
h_{fx} = head loss from a point "x" to the closed end of a multiple-outlet pipeline (feet)
$(H_f)_1$ = pressure-head loss from pipe friction for the manifold (feet)
$(H_f)_2$ = estimate being made of the pressure-head loss from pipe friction for the manifold (feet)
h_l = lateral inlet pressure that will give h_a (feet)
H_m = manifold inlet pressure head (feet)
$\triangle H_m$ = difference in pressure head along the manifold (feet)
$\triangle H_m'$ = amount the manifold inlet pressure differs from h_1 (feet)
$(\triangle H_m)_a$ = allowable manifold pressure variation (feet)
h_n = pressure head that will give the q_n required to satisfy the EU (feet)
H_r = ratio between fertilizing time and time of actual irrigating per irrigation cycle
$\triangle H_s$ = allowable subunit pressure-head variation that will give an EU reasonably close to the desired design value (feet)

h^1 = working pressure of the secondary chamber (feet)
h_1, h_2 = pressure heads corresponding to q_1, q_2, respectively (pounds per square inch)

i = annual interest rate
I_f = maximum allowable irrigation interval (days)
I_f = design irrigation interval (days)

j = dimensionless allowable head-loss ratio
J = head-loss gradient of a pipe (feet per 100 feet)
j' = $(\triangle H_m)_a$ value properly scaled for the manifold under study (feet)
J' = equivalent head-loss gradient of the lateral with emitters (feet per 100 feet)
J_l = head-loss gradient of the larger pipe (feet per 100 feet)
J_s = head-loss gradient of the smaller pipe (feet per 100 feet)
J_x = J value from Appendix B for the largest flow rate in the table for the required pipe size (feet per 100 feet)
JF' = scalar ratio for field shape
J'F = friction gradient found in step 1 of the graphical solution

k = scale factor for adjusting manifold pressure-head values taken from standard manifold curves
k_d = constant of proportionality (discharge coefficient) that characterizes each emitter
K_f = friction head-loss coefficient for a specific fitting

l = length of a lateral (feet)
L = length of a pipeline (feet)
l' = equivalent length of the lateral with emitter (feet)
l_a = original lateral pipe length (feet)
l_b = new lateral pipe length (feet)
l_c = length of the flow path in the emitter (feet)
L_d = length of pipe with diameter d (feet)
L_m = length of a single manifold (feet)
L_n = net leaching requirement for net application (inches)
L_N = annual leaching requirement for net seasonal application (inches)
L_p = length of a pair of manifolds (feet)
L_s = length of the smaller pipe that will increase the head loss by $\triangle H$ (feet)
LR_t = leaching requirement ratio

L_1 = length of pipe in the original manifold (feet)
L_2 = length of pipe in the manifold for which $(H_f)_2$ is being estimated (feet)

m = number of orifices in the secondary chamber per orifice in the main chamber
m′ = number of orifices in series in the emitter
M_{ad} = management-allowed deficit, which is the desired soil-moisture deficit at the time of irrigation (percent)
MLIP = minimum lateral inlet pressure (pounds per square inch)
average MLIP = average of the individual MLIP's along each manifold (pounds per square inch)
minimum MLIP = lowest lateral inlet pressure in the system (pounds per square inch)

n = number of emitters in the sample
n = expected life of the item (years)
N = number of operating stations
n_e = number of emitters along the lateral
$(n_p)_a$ = number of plants in the average row in the subunit
$(n_p)_c$ = number of plants in the row at the closed end of the manifold
n_r = number of row (or lateral) spacings served by the manifold
N_R = Reynolds number
$(n_r)_p$ = number of row (or lateral) spacings served from a common inlet point

P_c = pipe cost (dollars per pound)
P_s = average horizontal area shaded by the crop canopy as a percentage of the total crop area (percent)
P_u = unit of power
P_{uc} = unit cost of power (dollars per kilowatt hour)
P_w = average horizontal area wetted in the top part of the crop root zone as a percentage of the total crop area (percent)
PE_{lq} = potential application efficiency of the lower quarter
PS = perimeter of the area directly wetted by a sprayer (feet)
PW(r) = present worth factor with energy cost rising at rate r

q = emitter discharge rate (gallons per hour)
$\bar{q}$ = average discharge rate of the emitter sampled (gallons per hour)

Q = flow rate in the pipe (gallons per minute)
q_a = average of design emitter discharge rate (gallons per hour)
q_a' = average of all the field-data emitter discharges (gallons per hour)
q_c = rate of injection of the chemical into the system (gallons per hour)
q_d = upper limit flow rate for the pipe with diameter d (gallons per minute)
q_{d-1} = upper limit flow rate for the pipe with the next smaller diameter (gallons per minute)
q_f = rate of injection of liquid fertilizer into the system (gallons per hour)
q_l = lateral flow rate (gallons per minute)
$(q_l)_a$ = average lateral (pair) flow rate along the manifold (gallons per minute)
$(q_l)_c$ = flow rate into the lateral (pair) at the closed end of the manifold (gallons per minute)
q_{lp} = flow rate for pair of laterals (gallons per minute)
q_m = flow rate in the manifold (gallons per minute)
q_n = minimum emission rate computed from the minimum pressure in the system (gallons per hour)
q_n' = average discharge of the lowest quarter of the field-data discharge reading (gallons per hour)
Q_s = total system capacity or flow rate (gallons per minute)
Q_s' = adjusted flow rate for entering the economic design chart (gallons per minute)
Q_s'' = modified adjusted system flow rate (gallons per minute)
Q_t = average pump-operating time per season (hours)
q_x = largest flow rate (Q) in the respective table for pipe size in Appendix B (gallons per minute)
q_1 = flow rate in the original manifold (gallons per minute)
q_2 = flow rate in the manifold for which $(H_f)_2$ is being estimated (gallons per minute)
q_1, q_2 = discharges (gallons per hour)
$q_1, q_2 \ldots q_n$ = individual emitter discharge rates (gallons per hour)

r = annual rate of rising energy cost
R_e = effective rainfall during the growing season (inches)
R_e' = effective rainfall since the last irrigation (inches)

RZD = depth of the soil profile occupied by plant roots (feet)

S = unbiased standard deviation of the discharge rates of the sample
S = average slope of the ground line (percent)
S = slope of the manifold or lateral (feet per foot)
S′ = unusable slope component, which is the amount the friction curve needs to be raised (feet)
S′ = elevation (due to the slope, S, along the manifold) properly scaled for the manifold under study (feet)
S_e = spacing between emitters or emission points along a line (feet)
S_e' = optimum emitter spacing; drip emitter spacing that provides 80 percent of the wetted diameter estimated from field tests or table 7–2 (feet)
S_f = shape factor of the subunit
S_l = lateral spacing (feet)
S_m = manifold spacing (feet)
S_{md} = soil moisture deficit; difference between field capacity and the actual soil moisture in the root zone soil at any given time (inches)
S_p = plant spacing in the row (feet)
S_r = row spacing (feet)
S_w = width of the wetted strip (feet)
sg = specific gravity of the chemical concentrate

T_a = irrigation application time required during the peak use period (hours per day)
T_d = average daily transpiration rate for the month of greatest water use (inches per day)
T_r = peak-use period transpiration ratio
T_R = seasonal transpiration ratio
T_s = seasonal transpiration (inches)
TDH = total dynamic head (feet)
TDR = temperature-discharge ratio

U = seasonal total crop consumptive use (inches)
u_d = average daily consumptive-use rate for the month of greatest overall water use (inches per day)
u_m = total consumptive use rate for month (inches)

v = coefficient of manufacturing variation of the emitter
v = velocity of flow in the pipe (feet per second)
V_i = gross seasonal volume of irrigation water required (acre-feet)
V_s = system coefficient of manufacturing variation
$V^2/2g$ = velocity head: the energy head from the velocity of flow (feet)

W_s = residual stored moisture from off-season precipitation (inches)
WHC = water-holding capacity of the soil (inches per foot)

x = emitter discharge exponent
x = any position along the length
x = distance from the closed end (feet)
x/L = relative distance from the closed downstream end compared to the total length of a pair of laterals or manifolds

Y = theoretical reduction in yield (percent)
Y = tangent location

z = location of the inlet to the pair of laterals that gives equal minimum pressures in both the uphill and downhill members (ratio of the length of the downhill lateral to L)

ν = kinematic viscosity of water (feet squared per second)

Appendix B—Pipe Friction-Loss Tables (Smallest Standard Dimension Ratio Numbers)

Appendix Table 7–1.—Friction loss in trickle irrigation hose, nominal diameter 0.580 in.

[Inside diameter 0.580 in., discharge increment 0.05 gal/min]

Flow (Q) gal/min	Flow (Q) gal/hr	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (Q) gal/hr	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (Q) gal/hr	Friction loss (J) ft/100 ft
.05	3.00	.03	2.75	165.00	9.98	5.40	324.00	32.63
.10	6.00	.05	2.80	168.00	10.30	5.45	327.00	33.15
.15	9.00	.08	2.85	171.00	10.62	5.50	330.00	33.70
.20	12.00	.11	2.90	174.00	10.95	5.55	333.00	34.24
.25	15.00	.14	2.95	177.00	11.28	5.60	336.00	34.79
.30	18.00	.17	3.00	180.00	11.62	5.65	339.00	35.34
.35	21.00	.20	3.05	183.00	11.96	5.70	342.00	35.89
.40	24.00	.37	3.10	186.00	12.30	5.75	345.00	36.45
.45	27.00	.45	3.15	189.00	12.65	5.80	348.00	37.01
.50	30.00	.53	3.20	192.00	13.01	5.85	351.00	37.58
.55	33.00	.62	3.25	195.00	13.36	5.90	354.00	38.15
.60	36.00	.72	3.30	198.00	13.73	5.95	357.00	38.72
.65	39.00	.83	3.35	201.00	14.09	6.00	360.00	39.30
.70	42.00	.94	3.40	204.00	14.46	6.05	363.00	39.88
.75	45.00	1.06	3.45	207.00	14.84	6.10	366.00	40.46
.80	48.00	1.18	3.50	210.00	15.22	6.15	369.00	41.05
.85	51.00	1.31	3.55	213.00	15.60	6.20	372.00	41.64
.90	54.00	1.45	3.60	216.00	15.99	6.25	375.00	42.24
.95	57.00	1.59	3.65	219.00	16.38	6.30	378.00	42.84
1.00	60.00	1.73	3.70	222.00	16.77	6.35	381.00	43.44
1.05	63.00	1.88	3.75	225.00	17.17	6.40	384.00	44.05
1.10	66.00	2.04	3.80	228.00	17.58	6.45	387.00	44.66
1.15	69.00	2.20	3.85	231.00	17.99	6.50	390.00	45.27
1.20	72.00	2.37	3.90	234.00	18.40	6.55	393.00	45.89
1.25	75.00	2.54	3.95	237.00	18.81	6.60	396.00	46.51
1.30	78.00	2.72	4.00	240.00	19.23	6.65	399.00	47.13
1.35	81.00	2.90	4.05	243.00	19.66	6.70	402.00	47.76
1.40	84.00	3.09	4.10	246.00	20.09	6.75	405.00	48.40
1.45	87.00	3.28	4.15	249.00	20.52	6.80	408.00	49.03
1.50	90.00	3.48	4.20	252.00	20.96	6.85	411.00	49.67
1.55	93.00	3.68	4.25	255.00	21.40	6.90	414.00	50.32
1.60	96.00	3.89	4.30	258.00	21.84	6.95	417.00	50.96
1.65	99.00	4.10	4.35	261.00	22.29	7.00	420.00	51.61
1.70	102.00	4.32	4.40	264.00	22.74	7.05	423.00	52.27
1.75	105.00	4.54	4.45	267.00	23.20	7.10	426.00	52.93
1.80	108.00	4.77	4.50	270.00	23.66	7.15	429.00	53.59
1.85	111.00	5.00	4.55	273.00	24.12	7.20	432.00	54.25
1.90	114.00	5.24	4.60	276.00	24.59	7.25	435.00	54.92
1.95	117.00	5.48	4.65	279.00	25.07	7.30	438.00	55.60
2.00	120.00	5.73	4.70	282.00	25.54	7.35	441.00	56.27
2.05	123.00	5.98	4.75	285.00	26.02	7.40	444.00	56.95
2.10	126.00	6.24	4.80	288.00	26.51	7.45	447.00	57.64
2.15	129.00	6.50	4.85	291.00	27.00	7.50	450.00	58.32
2.20	132.00	6.76	4.90	294.00	27.49	7.55	453.00	59.01
2.25	135.00	7.03	4.95	297.00	27.98	7.60	456.00	59.71
2.30	138.00	7.31	5.00	300.00	28.49	7.65	459.00	60.41
2.35	141.00	7.58	5.05	303.00	28.99	7.70	462.00	61.11
2.40	144.00	7.87	5.10	306.00	29.50	7.75	465.00	61.81
2.45	147.00	8.16	5.15	309.00	30.01	7.80	468.00	62.52
2.50	150.00	8.45	5.20	312.00	30.52	7.85	471.00	63.23
2.55	153.00	8.75	5.25	315.00	31.04	7.90	474.00	63.95
2.60	156.00	9.05	5.30	318.00	31.57	7.95	477.00	64.67
2.65	159.00	9.35	5.35	321.00	32.09	8.00	480.00	65.39
2.70	162.00	9.66						

Appendix Table 7-2.—Friction loss in polyvinyl chloride (iron pipe size) hose, nominal diameter 1.25 in.

[Inside diameter 1.532 in., discharge increment 0.50 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
.50	.09	.01	29.50	5.13	6.42	58.00	10.09	21.50
1.00	.17	.01	30.00	5.22	6.62	58.50	10.18	21.84
1.50	.26	.04	30.50	5.31	6.81	59.00	10.27	22.17
2.00	.35	.06	31.00	5.39	7.01	59.50	10.35	22.51
2.50	.43	.09	31.50	5.48	7.22	60.00	10.44	22.85
3.00	.52	.12	32.00	5.57	7.42	60.50	10.53	23.20
3.50	.61	.15	32.50	5.65	7.63	61.00	10.61	23.54
4.00	.70	.19	33.00	5.74	7.84	61.50	10.70	23.89
4.50	.78	.24	33.50	5.83	8.05	62.00	10.79	24.24
5.00	.87	.28	34.00	5.92	8.27	62.50	10.87	24.59
5.50	.96	.33	34.50	6.00	8.49	63.00	10.96	24.95
6.00	1.04	.39	35.00	6.09	8.71	63.50	11.05	25.30
6.50	1.13	.45	35.50	6.18	8.93	64.00	11.13	25.66
7.00	1.22	.51	36.00	6.26	9.16	64.50	11.22	26.02
7.50	1.30	.57	36.50	6.35	9.39	65.00	11.31	26.39
8.00	1.39	.64	37.00	6.44	9.62	65.50	11.40	26.75
8.50	1.48	.71	37.50	6.52	9.85	66.00	11.48	27.12
9.00	1.57	.79	38.00	6.61	10.09	66.50	11.57	27.49
9.50	1.65	.87	38.50	6.70	10.32	67.00	11.66	27.86
10.00	1.74	.95	39.00	6.79	10.57	67.50	11.74	28.24
10.50	1.83	1.03	39.50	6.87	10.81	68.00	11.83	28.62
11.00	1.91	1.12	40.00	6.96	11.05	68.50	11.92	29.00
11.50	2.00	1.21	40.50	7.05	11.30	69.00	12.00	29.38
12.00	2.09	1.31	41.00	7.13	11.55	69.50	12.09	29.76
12.50	2.17	1.40	41.50	7.22	11.81	70.00	12.18	30.15
13.00	2.26	1.50	42.00	7.31	12.06	70.50	12.27	30.54
13.50	2.35	1.61	42.50	7.39	12.32	71.00	12.35	30.93
14.00	2.44	1.71	43.00	7.48	12.58	71.50	12.44	31.32
14.50	2.52	1.82	43.50	7.57	12.84	72.00	12.53	31.71
15.00	2.61	1.93	44.00	7.66	13.11	72.50	12.61	32.11
15.50	2.70	2.05	44.50	7.74	13.38	73.00	12.70	32.51
16.00	2.78	2.17	45.00	7.83	13.65	73.50	12.79	32.91
16.50	2.87	2.29	45.50	7.92	13.92	74.00	12.87	33.32
17.00	2.96	2.41	46.00	8.00	14.19	74.50	12.96	33.72
17.50	3.04	2.54	46.50	8.09	14.47	75.00	13.05	34.13
18.00	3.13	2.67	47.00	8.18	14.75	75.50	13.14	34.54
18.50	3.22	2.80	47.50	8.26	15.03	76.00	13.22	34.95
19.00	3.31	2.94	48.00	8.35	15.32	76.50	13.31	35.37
19.50	3.39	3.08	48.50	8.44	15.60	77.00	13.40	35.79
20.00	3.48	3.22	49.00	8.53	15.89	77.50	13.48	36.20
20.50	3.57	3.36	49.50	8.61	16.19	78.00	13.57	36.63
21.00	3.65	3.51	50.00	8.70	16.48	78.50	13.66	37.05
21.50	3.74	3.66	50.50	8.79	16.78	79.00	13.74	37.48
22.00	3.83	3.81	51.00	8.87	17.07	79.50	13.83	37.90
22.50	3.91	3.97	51.50	8.96	17.38	80.00	13.92	38.33
23.00	4.00	4.12	52.00	9.05	17.68	80.50	14.01	38.77
23.50	4.09	4.28	52.50	9.13	17.99	81.00	14.09	39.20
24.00	4.18	4.45	53.00	9.22	18.29	81.50	14.18	39.64
24.50	4.26	4.61	53.50	9.31	18.60	82.00	14.27	40.08
25.00	4.35	4.78	54.00	9.40	18.92	82.50	14.35	40.52
25.50	4.44	4.95	54.50	9.48	19.23	83.00	14.44	40.96
26.00	4.52	5.13	55.00	9.57	19.55	83.50	14.53	41.41
26.50	4.61	5.31	55.50	9.66	19.87	84.00	14.61	41.86
27.00	4.70	5.48	56.00	9.74	20.19	84.50	14.70	42.31
27.50	4.78	5.67	56.50	9.83	20.52	85.00	14.79	42.76
28.00	4.87	5.85	57.00	9.92	20.84	85.50	14.88	43.21
28.50	4.96	6.04	57.50	10.00	21.17	86.00	14.96	43.67
29.00	5.05	6.23						

Appendix Table 7–3.—Friction loss in trickle irrigation hose, nominal diameter 0.700 in.

[Inside diameter 0.700 in., discharge increment 0.10 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
.10	6.00	.03	5.50	330.00	13.76	10.80	648.00	45.38
.20	12.00	.05	5.60	336.00	14.20	10.90	654.00	46.13
.30	18.00	.08	5.70	342.00	14.65	11.00	660.00	46.89
.40	24.00	.11	5.80	348.00	15.11	11.10	666.00	47.65
.50	30.00	.22	5.90	354.00	15.57	11.20	672.00	48.41
.60	36.00	.30	6.00	360.00	16.04	11.30	678.00	49.18
.70	42.00	.39	6.10	366.00	16.51	11.40	684.00	49.96
.80	48.00	.49	6.20	372.00	17.00	11.50	690.00	50.74
.90	54.00	.60	6.30	378.00	17.48	11.60	696.00	51.53
1.00	60.00	.71	6.40	384.00	17.97	11.70	702.00	52.32
1.10	66.00	.84	6.50	390.00	18.47	11.80	708.00	53.12
1.20	72.00	.98	6.60	396.00	18.98	11.90	714.00	53.92
1.30	78.00	1.12	6.70	402.00	19.49	12.00	720.00	54.73
1.40	84.00	1.27	6.80	408.00	20.00	12.10	726.00	55.54
1.50	90.00	1.43	6.90	414.00	20.53	12.20	732.00	56.36
1.60	96.00	1.60	7.00	420.00	21.05	12.30	738.00	57.19
1.70	102.00	1.78	7.10	426.00	21.59	12.40	744.00	58.02
1.80	108.00	1.96	7.20	432.00	22.13	12.50	750.00	58.85
1.90	114.00	2.15	7.30	438.00	22.67	12.60	756.00	59.69
2.00	120.00	2.35	7.40	444.00	23.22	12.70	762.00	60.54
2.10	126.00	2.56	7.50	450.00	23.78	12.80	768.00	61.39
2.20	132.00	2.77	7.60	456.00	24.35	12.90	774.00	62.25
2.30	138.00	3.00	7.70	462.00	24.92	13.00	780.00	63.11
2.40	144.00	3.23	7.80	468.00	25.49	13.10	786.00	63.97
2.50	150.00	3.46	7.90	474.00	26.07	13.20	792.00	64.85
2.60	156.00	3.71	8.00	480.00	26.66	13.30	798.00	65.72
2.70	162.00	3.96	8.10	486.00	27.25	13.40	804.00	66.61
2.80	168.00	4.22	8.20	492.00	27.85	13.50	810.00	67.49
2.90	174.00	4.48	8.30	498.00	28.45	13.60	816.00	68.39
3.00	180.00	4.76	8.40	504.00	29.06	13.70	822.00	69.29
3.10	186.00	5.04	8.50	510.00	29.68	13.80	828.00	70.19
3.20	192.00	5.33	8.60	516.00	30.30	13.90	834.00	71.10
3.30	198.00	5.62	8.70	522.00	30.93	14.00	840.00	72.01
3.40	204.00	5.92	8.80	528.00	31.56	14.10	846.00	72.93
3.50	210.00	6.23	8.90	534.00	32.20	14.20	852.00	73.85
3.60	216.00	6.54	9.00	540.00	32.84	14.30	858.00	74.78
3.70	222.00	6.86	9.10	546.00	33.49	14.40	864.00	75.72
3.80	228.00	7.19	9.20	552.00	34.15	14.50	870.00	76.66
3.90	234.00	7.53	9.30	558.00	34.81	14.60	876.00	77.60
4.00	240.00	7.87	9.40	564.00	35.47	14.70	882.00	78.55
4.10	246.00	8.21	9.50	570.00	36.14	14.80	888.00	79.51
4.20	252.00	8.57	9.60	576.00	36.82	14.90	894.00	80.47
4.30	258.00	8.93	9.70	582.00	37.51	15.00	900.00	81.44
4.40	264.00	9.30	9.80	588.00	38.19	15.10	906.00	82.41
4.50	270.00	9.67	9.90	594.00	38.89	15.20	912.00	83.38
4.60	276.00	10.05	10.00	600.00	39.59	15.30	918.00	84.36
4.70	282.00	10.44	10.10	606.00	40.29	15.40	924.00	85.35
4.90	294.00	11.23	10.20	612.00	41.00	15.50	930.00	86.34
5.00	300.00	11.64	10.30	618.00	41.72	15.60	936.00	87.34
5.10	306.00	12.05	10.40	624.00	42.44	15.70	942.00	88.34
5.20	312.00	12.47	10.50	630.00	43.17	15.80	948.00	89.34
5.30	318.00	12.89	10.60	636.00	43.90	15.90	954.00	90.36
5.40	324.00	13.32	10.70	642.00	44.64	16.00	960.00	91.37

Appendix Table 7–4.—Friction loss in trickle irrigation hose, nominal diameter 1.5 in.

[Inside diameter 1.754 in., discharge increment 1.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
1.00	.13	.01	58.00	7.70	11.24
2.00	.27	.03	59.00	7.83	11.59
3.00	.40	.06	60.00	7.96	11.95
4.00	.53	.10	61.00	8.10	12.31
5.00	.66	.15	62.00	8.23	12.67
6.00	.80	.20	63.00	8.36	13.04
7.00	.93	.27	64.00	8.49	13.41
8.00	1.06	.34	65.00	8.63	13.79
9.00	1.19	.41	66.00	8.76	14.17
10.00	1.33	.50	67.00	8.89	14.56
11.00	1.46	.59	68.00	9.03	14.95
12.00	1.59	.69	69.00	9.16	15.35
13.00	1.73	.79	70.00	9.29	15.75
14.00	1.86	.90	71.00	9.42	16.16
15.00	1.99	1.02	72.00	9.56	16.57
16.00	2.12	1.14	73.00	9.69	16.98
17.00	2.26	1.27	74.00	9.82	17.41
18.00	2.39	1.40	75.00	9.95	17.83
19.00	2.52	1.54	76.00	10.09	18.26
20.00	2.65	1.69	77.00	10.22	18.69
21.00	2.79	1.84	78.00	10.35	19.13
22.00	2.92	2.00	79.00	10.49	19.58
23.00	3.05	2.16	80.00	10.62	20.02
24.00	3.19	2.33	81.00	10.75	20.48
25.00	3.32	2.51	82.00	10.88	20.93
26.00	3.45	2.69	83.00	11.02	21.39
27.00	3.59	2.87	84.00	11.15	21.86
28.00	3.72	3.06	85.00	11.29	22.33
29.00	3.85	3.26	86.00	11.41	22.80
30.00	3.98	3.46	87.00	11.55	23.28
31.00	4.11	3.67	88.00	11.68	23.77
32.00	4.25	3.89	89.00	11.81	24.26
33.00	4.38	4.11	90.00	11.95	24.75
34.00	4.51	4.33	91.00	12.08	25.25
35.00	4.65	4.56	92.00	12.21	25.75
36.00	4.78	4.79	93.00	12.34	26.25
37.00	4.91	5.03	94.00	12.48	26.77
38.00	5.04	5.28	95.00	12.61	27.28
39.00	5.18	5.53	96.00	12.74	27.80
40.00	5.31	5.78	97.00	12.87	28.32
41.00	5.44	6.04	98.00	13.01	28.85
42.00	5.57	6.31	99.00	13.14	29.38
43.00	5.71	6.58	100.00	13.27	29.92
44.00	5.84	6.86	101.00	13.41	30.46
45.00	5.97	7.14	102.00	13.54	31.01
46.00	6.11	7.42	103.00	13.67	31.56
47.00	6.24	7.72	104.00	13.80	32.11
48.00	6.37	8.01	105.00	13.94	32.67
49.00	6.50	8.31	106.00	14.07	33.23
50.00	6.64	8.62	107.00	14.20	33.80
51.00	6.77	8.93	108.00	14.33	34.37
52.00	6.90	9.24	109.00	14.47	34.95
53.00	7.03	9.57	110.00	14.60	35.53
54.00	7.17	9.89	111.00	14.73	36.12
55.00	7.30	10.22	112.00	14.87	36.70
56.00	7.43	10.56	113.00	15.00	37.30
57.00	7.57	10.90			

Appendix Table 7–5.—Friction loss in trickle irrigation hose, nominal diameter 2 in.

[Inside diameter 2.193 in., discharge increment 1.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
1.00	.08	.00	60.00	5.09	4.10	118.00	10.02	13.79
2.00	.17	.01	61.00	5.18	4.22	119.00	10.10	14.01
3.00	.25	.02	62.00	5.26	4.34	120.00	10.19	14.22
4.00	.34	.04	63.00	5.35	4.47	121.00	10.27	14.43
5.00	.42	.05	64.00	5.43	4.60	122.00	10.36	14.65
6.00	.51	.07	65.00	5.52	4.73	123.00	10.44	14.88
7.00	.59	.09	66.00	5.60	4.86	124.00	10.53	15.03
8.00	.68	.12	67.00	5.69	4.99	125.00	10.61	15.30
9.00	.76	.14	68.00	5.77	5.13	126.00	10.70	15.52
10.00	.85	.17	69.00	5.86	5.26	127.00	10.78	15.75
11.00	.93	.20	70.00	5.94	5.40	128.00	10.87	15.97
12.00	1.02	.24	71.00	6.03	5.54	129.00	10.95	16.20
13.00	1.10	.27	72.00	6.11	5.68	130.00	11.04	16.42
14.00	1.19	.31	73.00	6.20	5.82	131.00	11.12	16.65
15.00	1.27	.35	74.00	6.28	5.96	132.00	11.21	16.83
16.00	1.36	.39	75.00	6.37	6.11	133.00	11.29	17.11
17.00	1.44	.44	76.00	6.45	6.26	134.00	11.38	17.35
18.00	1.53	.48	77.00	6.54	6.40	135.00	11.46	17.58
19.00	1.61	.53	78.00	6.62	6.55	136.00	11.55	17.82
20.00	1.70	.58	79.00	6.71	6.71	137.00	11.63	18.05
21.00	1.78	.63	80.00	6.79	6.86	138.00	11.72	18.29
22.00	1.87	.69	81.00	6.88	7.01	139.00	11.80	18.53
23.00	1.95	.74	82.00	6.96	7.17	140.00	11.89	18.77
24.00	2.04	.80	83.00	7.05	7.33	141.00	11.97	19.01
25.00	2.12	.86	84.00	7.13	7.49	142.00	12.06	19.26
26.00	2.21	.93	85.00	7.22	7.65	143.00	12.14	19.50
27.00	2.29	.99	86.00	7.30	7.81	144.00	12.23	19.75
28.00	2.38	1.05	87.00	7.39	7.97	145.00	12.31	20.00
29.00	2.46	1.12	88.00	7.47	8.14	146.00	12.40	20.25
30.00	2.55	1.19	89.00	7.56	8.31	147.00	12.48	20.50
31.00	2.63	1.26	90.00	7.64	8.47	148.00	12.57	20.75
32.00	2.72	1.34	91.00	7.73	8.64	149.00	12.65	21.01
33.00	2.80	1.41	92.00	7.81	8.82	150.00	12.74	21.26
34.00	2.89	1.49	93.00	7.90	8.99	151.00	12.82	21.52
35.00	2.97	1.57	94.00	7.98	9.16	152.00	12.91	21.78
36.00	3.06	1.65	95.00	8.07	9.34	153.00	12.99	22.04
37.00	3.14	1.73	96.00	8.15	9.52	154.00	13.08	22.30
38.00	3.23	1.81	97.00	8.24	9.69	155.00	13.16	22.56
39.00	3.31	1.90	98.00	8.32	9.88	156.00	13.25	22.82
40.00	3.40	1.99	99.00	8.41	10.06	157.00	13.33	23.09
41.00	3.48	2.08	100.00	8.49	10.24	158.00	13.42	23.35
42.00	3.57	2.17	101.00	8.58	10.43	159.00	13.50	23.62
43.00	3.65	2.26	102.00	8.66	10.61	160.00	13.59	23.89
44.00	3.74	2.36	103.00	8.75	10.80	161.00	13.67	24.16
45.00	3.82	2.45	104.00	8.83	10.99	162.00	13.76	24.43
46.00	3.91	2.55	105.00	8.92	11.18	163.00	13.84	24.70
47.00	3.99	2.65	106.00	9.00	11.37	164.00	13.92	24.98
48.00	4.08	2.75	107.00	9.09	11.57	165.00	14.01	25.26
49.00	4.16	2.85	108.00	9.17	11.76	166.00	14.09	25.53
50.00	4.25	2.96	109.00	9.25	11.96	167.00	14.18	25.81
51.00	4.33	3.06	110.00	9.34	12.16	168.00	14.26	26.09
52.00	4.42	3.17	111.00	9.42	12.36	169.00	14.35	26.37
53.00	4.50	3.28	112.00	9.51	12.56	170.00	14.43	26.65
54.00	4.59	3.39	113.00	9.59	12.76	171.00	14.52	26.94
55.00	4.67	3.51	114.00	9.68	12.96	172.00	14.60	27.22
56.00	4.75	3.62	115.00	9.76	13.17	173.00	14.69	27.51
57.00	4.84	3.74	116.00	9.85	13.39	174.00	14.77	27.80
58.00	4.92	3.86	117.00	9.93	13.58	175.00	14.86	28.09
59.00	5.01	3.98						

Appendix Table 7–6.—Friction loss in trickle irrigation hose, nominal diameter 2.5 in.

[Inside diameter 2.655 in., discharge increment 2.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
2.00	.12	.00	88.00	5.10	3.26	174.00	10.08	11.09
4.00	.23	.01	90.00	5.21	3.39	176.00	10.20	11.32
6.00	.35	.03	92.00	5.33	3.52	178.00	10.31	11.56
8.00	.46	.05	94.00	5.45	3.66	180.00	10.43	11.79
10.00	.58	.07	96.00	5.56	3.80	182.00	10.54	12.03
12.00	.70	.10	98.00	5.68	3.95	184.00	10.66	12.27
14.00	.81	.13	100.00	5.79	4.09	186.00	10.77	12.51
16.00	.93	.16	102.00	5.91	4.24	188.00	10.89	12.75
18.00	1.04	.19	104.00	6.02	4.39	190.00	11.01	13.00
20.00	1.16	.23	106.00	6.14	4.55	192.00	11.12	13.25
22.00	1.27	.28	108.00	6.26	4.70	194.00	11.24	13.50
24.00	1.39	.32	110.00	6.37	4.86	196.00	11.35	13.75
26.00	1.51	.37	112.00	6.49	5.02	198.00	11.47	14.01
28.00	1.62	.42	114.00	6.60	5.18	200.00	11.59	14.26
30.00	1.74	.48	116.00	6.72	5.34	202.00	11.70	14.52
32.00	1.85	.54	118.00	6.84	5.51	204.00	11.82	14.78
34.00	1.97	.60	120.00	6.95	5.68	206.00	11.93	15.05
36.00	2.09	.66	122.00	7.07	5.85	208.00	12.05	15.31
38.00	2.20	.73	124.00	7.18	6.02	210.00	12.17	15.58
40.00	2.32	.80	126.00	7.30	6.20	212.00	12.28	15.85
42.00	2.43	.87	128.00	7.41	6.38	214.00	12.40	16.12
44.00	2.55	.94	130.00	7.53	6.56	216.00	12.51	16.39
46.00	2.66	1.02	132.00	7.65	6.74	218.00	12.63	16.67
48.00	2.78	1.10	134.00	7.76	6.93	220.00	12.74	16.94
50.00	2.90	1.19	136.00	7.88	7.11	222.00	12.86	17.22
52.00	3.01	1.27	138.00	7.99	7.30	224.00	12.98	17.51
54.00	3.13	1.36	140.00	8.11	7.50	226.00	13.09	17.79
56.00	3.24	1.45	142.00	8.23	7.69	228.00	13.21	18.08
58.00	3.36	1.54	144.00	8.34	7.88	230.00	13.32	18.36
60.00	3.48	1.64	146.00	8.46	8.08	232.00	13.44	18.65
62.00	3.59	1.74	148.00	8.57	8.28	234.00	13.56	18.95
64.00	3.71	1.84	150.00	8.69	8.49	236.00	13.67	19.24
66.00	3.82	1.95	152.00	8.81	8.69	238.00	13.79	19.54
68.00	3.94	2.05	154.00	8.92	8.90	240.00	13.90	19.83
70.00	4.06	2.16	156.00	9.04	9.11	242.00	14.02	20.13
72.00	4.17	2.27	158.00	9.15	9.32	244.00	14.13	20.44
74.00	4.29	2.39	160.00	9.27	9.53	246.00	14.25	20.74
76.00	4.40	2.50	162.00	9.38	9.75	248.00	14.37	21.05
78.00	4.52	2.62	164.00	9.50	9.97	250.00	14.48	21.35
80.00	4.63	2.74	166.00	9.62	10.19	252.00	14.60	21.67
82.00	4.75	2.87	168.00	9.73	10.41	254.00	14.71	21.98
84.00	4.87	2.99	170.00	9.85	10.64	256.00	14.83	22.29
86.00	4.98	3.12	172.00	9.96	10.86	258.00	14.95	22.61

Appendix Table 7-7.—Friction loss in trickle irrigation hose, nominal diameter 3 in.

[Inside diameter 3.284 in., discharge increment 2.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
2.00	.08	.00	110.00	4.16	1.75	218.00	8.25	6.00
4.00	.15	.01	112.00	4.24	1.81	220.00	8.33	6.10
6.00	.23	.01	114.00	4.32	1.87	222.00	8.41	6.20
8.00	.30	.02	116.00	4.39	1.93	224.00	8.48	6.30
10.00	.38	.03	118.00	4.47	1.99	226.00	8.56	6.40
12.00	.45	.03	120.00	4.54	2.05	223.00	8.63	6.50
14.00	.53	.05	122.00	4.62	2.11	230.00	8.71	6.61
16.00	.61	.06	124.00	4.70	2.17	232.00	8.79	6.71
18.00	.68	.07	126.00	4.77	2.24	234.00	8.86	6.82
20.00	.76	.09	128.00	4.85	2.30	236.00	8.94	6.92
22.00	.83	.10	130.00	4.92	2.37	238.00	9.01	7.03
24.00	.91	.12	132.00	5.00	2.43	240.00	9.09	7.14
26.00	.98	.14	134.00	5.07	2.50	242.00	9.16	7.24
28.00	1.06	.15	136.00	5.15	2.56	244.00	9.24	7.35
30.00	1.14	.17	138.00	5.23	2.63	246.00	9.31	7.46
32.00	1.21	.19	140.00	5.30	2.70	248.00	9.39	7.57
34.00	1.29	.22	142.00	5.38	2.77	250.00	9.47	7.68
36.00	1.36	.24	144.00	5.45	2.84	252.00	9.54	7.79
38.00	1.44	.26	146.00	5.53	2.91	254.00	9.62	7.91
40.00	1.51	.29	148.00	5.60	2.99	256.00	9.69	8.02
42.00	1.59	.32	150.00	5.68	3.06	258.00	9.77	8.13
44.00	1.67	.34	152.00	5.76	3.13	260.00	9.84	8.25
46.00	1.74	.37	154.00	5.83	3.21	262.00	9.92	8.36
48.00	1.82	.40	156.00	5.91	3.28	264.00	10.00	8.48
50.00	1.89	.43	158.00	5.98	3.36	266.00	10.07	8.59
52.00	1.97	.46	160.00	6.06	3.44	268.00	10.15	8.71
54.00	2.04	.49	162.00	6.13	3.51	270.00	10.22	8.83
56.00	2.12	.53	164.00	6.21	3.59	272.00	10.30	8.95
58.00	2.20	.56	166.00	6.28	3.67	274.00	10.37	9.07
60.00	2.27	.59	168.00	6.36	3.75	276.00	10.45	9.19
62.00	2.35	.63	170.00	6.44	3.83	278.00	10.53	9.31
64.00	2.42	.67	172.00	6.51	3.91	280.00	10.60	9.43
66.00	2.50	.70	174.00	6.59	4.00	282.00	10.68	9.55
68.00	2.57	.74	176.00	6.66	4.08	284.00	10.75	9.67
70.00	2.65	.78	178.00	6.74	4.16	286.00	10.83	9.80
72.00	2.73	.82	180.00	6.82	4.25	288.00	10.90	9.92
74.00	2.80	.86	182.00	6.89	4.33	290.00	10.98	10.05
76.00	2.88	.90	184.00	6.97	4.42	292.00	11.06	10.17
78.00	2.95	.95	186.00	7.04	4.51	294.00	11.13	10.30
80.00	3.03	.99	189.00	7.12	4.59	296.00	11.21	10.43
82.00	3.10	1.04	190.00	7.19	4.68	298.00	11.28	10.55
84.00	3.18	1.08	192.00	7.27	4.77	300.00	11.36	10.68
86.00	3.26	1.13	194.00	7.35	4.86	302.00	11.43	10.81
88.00	3.33	1.18	196.00	7.42	4.95	304.00	11.51	10.94
90.00	3.41	1.22	198.00	7.50	5.04	306.00	11.59	11.07
92.00	3.48	1.27	200.00	7.57	5.13	308.00	11.66	11.20
94.00	3.56	1.32	202.00	7.65	5.23	310.00	11.74	11.34
96.00	3.63	1.37	204.00	7.72	5.32	312.00	11.81	11.47
98.00	3.71	1.43	206.00	7.80	5.42	314.00	11.89	11.60
100.00	3.79	1.48	208.00	7.88	5.51	316.00	11.96	11.74
102.00	3.86	1.53	210.00	7.95	5.61	318.00	12.04	11.87
104.00	3.94	1.59	212.00	8.03	5.70	320.00	12.12	12.01
106.00	4.01	1.64	214.00	8.10	5.80	322.00	12.19	12.14
108.00	4.09	1.70	216.00	8.18	5.90	324.00	12.27	12.28

Appendix Table 7–8.—Friction loss in trickle irrigation hose, nominal diameter 4 in.

[Inside diameter 4.280 in., discharge increment 5.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
5.00	.11	.00	230.00	5.13	1.85	455.00	10.14	6.35
10.00	.22	.01	235.00	5.24	1.92	460.00	10.25	6.48
15.00	.33	.01	240.00	5.35	2.00	465.00	10.37	6.61
20.00	.45	.02	245.00	5.46	2.07	470.00	10.48	6.74
25.00	.56	.04	250.00	5.57	2.15	475.00	10.59	6.87
30.00	.67	.05	255.00	5.68	2.23	480.00	10.70	7.00
35.00	.78	.06	260.00	5.80	2.31	485.00	10.81	7.13
40.00	.89	.08	265.00	5.91	2.39	490.00	10.92	7.26
45.00	1.00	.10	270.00	6.02	2.47	495.00	11.03	7.40
50.00	1.11	.12	275.00	6.13	2.55	500.00	11.15	7.53
55.00	1.23	.14	280.00	6.24	2.64	505.00	11.26	7.67
60.00	1.34	.17	285.00	6.35	2.72	510.00	11.37	7.81
65.00	1.45	.19	290.00	6.46	2.81	515.00	11.48	7.95
70.00	1.56	.22	295.00	6.58	2.90	520.00	11.59	8.09
75.00	1.67	.25	300.00	6.69	2.99	525.00	11.70	8.23
80.00	1.78	.28	305.00	6.80	3.08	530.00	11.81	8.38
85.00	1.89	.31	310.00	6.91	3.17	535.00	11.93	8.52
90.00	2.01	.34	315.00	7.02	3.26	540.00	12.04	8.66
95.00	2.12	.38	320.00	7.13	3.36	545.00	12.15	8.81
100.00	2.23	.42	325.00	7.24	3.45	550.00	12.26	8.96
105.00	2.34	.45	330.00	7.36	3.55	555.00	12.37	9.11
110.00	2.45	.49	335.00	7.47	3.65	560.00	12.48	9.26
115.00	2.56	.53	340.00	7.58	3.75	565.00	12.59	9.41
120.00	2.67	.58	345.00	7.69	3.85	570.00	12.71	9.56
125.00	2.79	.62	350.00	7.80	3.95	575.00	12.82	9.71
130.00	2.90	.66	355.00	7.91	4.05	580.00	12.93	9.86
135.00	3.01	.71	360.00	8.02	4.16	585.00	13.04	10.02
140.00	3.12	.76	365.00	8.14	4.26	590.00	13.15	10.18
145.00	3.23	.81	370.00	8.25	4.37	595.00	13.26	10.33
150.00	3.34	.86	375.00	8.36	4.47	600.00	13.37	10.49
155.00	3.46	.91	380.00	8.47	4.58	605.00	13.49	10.65
160.00	3.57	.96	385.00	8.58	4.69	610.00	13.60	10.81
165.00	3.68	1.02	390.00	8.69	4.80	615.00	13.71	10.97
170.00	3.79	1.07	395.00	8.81	4.92	620.00	13.82	11.14
175.00	3.90	1.13	400.00	8.92	5.03	625.00	13.93	11.30
180.00	4.01	1.19	405.00	9.03	5.14	630.00	14.04	11.46
185.00	4.12	1.25	410.00	9.14	5.26	635.00	14.16	11.63
190.00	4.24	1.31	415.00	9.25	5.38	640.00	14.27	11.80
195.00	4.35	1.38	420.00	9.36	5.49	645.00	14.38	11.96
200.00	4.46	1.44	425.00	9.47	5.61	650.00	14.49	12.13
205.00	4.57	1.50	430.00	9.59	5.73	655.00	14.60	12.30
210.00	4.68	1.57	435.00	9.70	5.85	660.00	14.71	12.48
215.00	4.79	1.64	440.00	9.81	5.98	665.00	14.82	12.65
220.00	4.90	1.71	445.00	9.92	6.10	670.00	14.94	12.82
225.00	5.02	1.78	450.00	10.03	6.22			

Appendix Table 7–9.—Friction loss in trickle irrigation hose, nominal diameter 6 in.

[Inside diameter 6.301 in., discharge increment 5.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
5.00	.05	.00	275.00	2.83	.40	545.00	5.61	1.37
10.00	.10	.00	280.00	2.88	.41	550.00	5.66	1.39
15.00	.15	.00	285.00	2.93	.43	555.00	5.71	1.42
20.00	.21	.00	290.00	2.98	.44	560.00	5.76	1.44
25.00	.26	.01	295.00	3.03	.45	565.00	5.81	1.46
30.00	.31	.01	300.00	3.09	.47	570.00	5.86	1.49
35.00	.36	.01	305.00	3.14	.48	575.00	5.91	1.51
40.00	.41	.01	310.00	3.19	.49	580.00	5.97	1.53
45.00	.46	.02	315.00	3.24	.51	585.00	6.02	1.56
50.00	.51	.02	320.00	3.29	.52	590.00	6.07	1.58
55.00	.57	.02	325.00	3.34	.54	595.00	6.12	1.61
60.00	.62	.03	330.00	3.39	.55	600.00	6.17	1.63
65.00	.67	.03	335.00	3.45	.57	605.00	6.22	1.65
70.00	.72	.03	340.00	3.50	.58	610.00	6.27	1.68
75.00	.77	.04	345.00	3.55	.60	615.00	6.33	1.70
80.00	.82	.04	350.00	3.60	.62	620.00	6.38	1.73
85.00	.87	.05	355.00	3.65	.63	625.00	6.43	1.76
90.00	.93	.05	360.00	3.70	.65	630.00	6.48	1.78
95.00	.98	.06	365.00	3.75	.66	635.00	6.53	1.81
100.00	1.03	.07	370.00	3.81	.68	640.00	6.58	1.83
105.00	1.08	.07	375.00	3.86	.70	645.00	6.63	1.86
110.00	1.13	.08	380.00	3.91	.71	650.00	6.68	1.88
115.00	1.18	.08	385.00	3.96	.73	655.00	6.74	1.91
120.00	1.23	.09	390.00	4.01	.75	660.00	6.79	1.94
125.00	1.28	.10	395.00	4.06	.77	665.00	6.84	1.96
130.00	1.34	.10	400.00	4.11	.78	670.00	6.89	1.99
135.00	1.39	.11	405.00	4.17	.80	675.00	6.94	2.02
140.00	1.44	.12	410.00	4.22	.82	680.00	6.99	2.05
145.00	1.49	.13	415.00	4.27	.84	685.00	7.05	2.07
150.00	1.54	.13	420.00	4.32	.86	690.00	7.10	2.10
155.00	1.59	.14	425.00	4.37	.87	695.00	7.15	2.13
160.00	1.65	.15	430.00	4.42	.89	700.00	7.20	2.16
165.00	1.70	.16	435.00	4.47	.91	705.00	7.25	2.18
170.00	1.75	.17	440.00	4.53	.93	710.00	7.30	2.21
175.00	1.80	.18	445.00	4.58	.95	715.00	7.35	2.24
180.00	1.85	.19	450.00	4.63	.97	720.00	7.41	2.27
185.00	1.90	.20	455.00	4.68	.99	725.00	7.46	2.30
190.00	1.95	.21	460.00	4.73	1.01	730.00	7.51	2.33
195.00	2.01	.22	465.00	4.78	1.03	735.00	7.56	2.36
200.00	2.06	.23	470.00	4.83	1.05	740.00	7.61	2.38
205.00	2.11	.24	475.00	4.89	1.07	745.00	7.66	2.41
210.00	2.16	.25	480.00	4.94	1.09	750.00	7.71	2.44
215.00	2.21	.26	485.00	4.99	1.11	755.00	7.77	2.47
220.00	2.26	.27	490.00	5.04	1.13	760.00	7.82	2.50
225.00	2.31	.28	495.00	5.09	1.15	765.00	7.87	2.53
230.00	2.37	.29	500.00	5.14	1.17	770.00	7.92	2.56
235.00	2.42	.30	505.00	5.19	1.19	775.00	7.97	2.59
240.00	2.47	.31	510.00	5.25	1.21	780.00	8.02	2.62
245.00	2.52	.32	515.00	5.30	1.24	785.00	8.07	2.65
250.00	2.57	.34	520.00	5.35	1.26	790.00	8.13	2.68
255.00	2.62	.35	525.00	5.40	1.28	795.00	8.18	2.72
260.00	2.67	.36	530.00	5.45	1.30	800.00	8.23	2.75
265.00	2.73	.37	535.00	5.50	1.32	805.00	8.28	2.78
270.00	2.78	.39	540.00	5.55	1.35	810.00	8.33	2.81

Appendix Table 7-10.—Friction loss in trickle irrigation hose, nominal diameter 8 in.

[Inside diameter 8.205 in., discharge increment 10.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
10.00	.06	.00	550.00	3.34	.39	1090.00	6.61	1.35
20.00	.12	.00	560.00	3.40	.40	1100.00	6.67	1.37
30.00	.18	.00	570.00	3.46	.42	1110.00	6.73	1.40
40.00	.24	.00	580.00	3.52	.43	1120.00	6.79	1.42
50.00	.30	.01	590.00	3.58	.44	1130.00	6.85	1.44
60.00	.36	.01	600.00	3.64	.46	1140.00	6.91	1.47
70.00	.42	.01	610.00	3.70	.47	1150.00	6.99	1.49
80.00	.49	.01	620.00	3.76	.49	1160.00	7.04	1.51
90.00	.55	.02	630.00	3.82	.50	1170.00	7.10	1.53
100.00	.61	.02	640.00	3.88	.51	1180.00	7.16	1.56
110.00	.67	.02	650.00	3.94	.53	1190.00	7.22	1.58
120.00	.73	.03	660.00	4.00	.54	1200.00	7.28	1.60
130.00	.79	.03	670.00	4.06	.56	1210.00	7.33	1.64
140.00	.85	.03	680.00	4.12	.57	1220.00	7.39	1.66
150.00	.91	.04	690.00	4.19	.59	1230.00	7.45	1.68
160.00	.97	.04	700.00	4.25	.61	1240.00	7.51	1.71
170.00	1.03	.05	710.00	4.31	.62	1250.00	7.58	1.73
180.00	1.09	.05	720.00	4.37	.64	1260.00	7.64	1.76
190.00	1.15	.06	730.00	4.43	.65	1270.00	7.70	1.78
200.00	1.21	.06	740.00	4.49	.67	1280.00	7.76	1.81
210.00	1.27	.07	750.00	4.55	.69	1290.00	7.82	1.83
220.00	1.33	.08	760.00	4.61	.70	1300.00	7.89	1.86
230.00	1.40	.08	770.00	4.67	.72	1310.00	7.95	1.89
240.00	1.46	.09	780.00	4.73	.74	1320.00	8.01	1.91
250.00	1.52	.09	790.00	4.79	.75	1330.00	8.07	1.94
260.00	1.58	.10	800.00	4.85	.77	1340.00	8.13	1.97
270.00	1.64	.11	810.00	4.91	.79	1350.00	8.19	1.99
280.00	1.70	.12	820.00	4.97	.81	1360.00	8.25	2.02
290.00	1.76	.12	830.00	5.03	.82	1370.00	8.31	2.05
300.00	1.82	.13	840.00	5.10	.84	1380.00	8.37	2.07
310.00	1.88	.14	850.00	5.16	.86	1390.00	8.43	2.10
320.00	1.94	.15	860.00	5.22	.88	1400.00	8.49	2.13
330.00	2.00	.16	870.00	5.28	.90	1410.00	8.55	2.16
340.00	2.06	.16	880.00	5.34	.92	1420.00	8.61	2.18
350.00	2.12	.17	890.00	5.40	.93	1430.00	8.67	2.21
360.00	2.18	.18	900.00	5.46	.95	1440.00	8.73	2.24
370.00	2.24	.19	910.00	5.52	.97	1450.00	8.80	2.27
380.00	2.30	.20	920.00	5.58	.99	1460.00	8.86	2.30
390.00	2.37	.21	930.00	5.64	1.01	1470.00	8.92	2.33
400.00	2.43	.22	940.00	5.70	1.03	1480.00	8.98	2.36
410.00	2.49	.23	950.00	5.76	1.05	1490.00	9.04	2.38
420.00	2.55	.24	960.00	5.82	1.07	1500.00	9.10	2.41
430.00	2.61	.25	970.00	5.88	1.09	1510.00	9.16	2.44
440.00	2.67	.26	980.00	5.94	1.11	1520.00	9.22	2.47
450.00	2.73	.27	990.00	6.00	1.13	1530.00	9.28	2.50
460.00	2.79	.28	1000.00	6.07	1.15	1540.00	9.34	2.53
470.00	2.85	.29	1010.00	6.13	1.18	1550.00	9.40	2.56
480.00	2.91	.31	1020.00	6.19	1.20	1560.00	9.46	2.59
490.00	2.97	.32	1030.00	6.25	1.22	1570.00	9.52	2.62
500.00	3.03	.33	1040.00	6.31	1.24	1580.00	9.58	2.65
510.00	3.09	.34	1050.00	6.37	1.26	1590.00	9.64	2.68
520.00	3.15	.35	1060.00	6.43	1.28	1600.00	9.70	2.71
530.00	3.21	.37	1070.00	6.49	1.31	1610.00	9.77	2.75
540.00	3.28	.38	1080.00	6.55	1.33	1620.00	9.83	2.78

Appendix Table 7-11.—Friction loss in trickle irrigation hose, nominal diameter 10 in.

[Inside diameter 10.226 in., discharge increment 10.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
10.00	.04	.00	600.00	2.34	.16	1190.00	4.65	.55	1780.00	6.95	1.14
20.00	.08	.00	610.00	2.38	.16	1200.00	4.69	.56	1790.00	6.99	1.15
30.00	.12	.00	620.00	2.42	.17	1210.00	4.72	.57	1800.00	7.03	1.16
40.00	.16	.00	630.00	2.46	.17	1220.00	4.76	.57	1810.00	7.07	1.18
50.00	.20	.00	640.00	2.50	.18	1230.00	4.80	.58	1820.00	7.11	1.19
60.00	.23	.00	650.00	2.54	.18	1240.00	4.84	.59	1830.00	7.15	1.20
70.00	.27	.00	660.00	2.58	.19	1250.00	4.88	.60	1840.00	7.19	1.21
80.00	.31	.00	670.00	2.62	.19	1260.00	4.92	.61	1850.00	7.22	1.22
90.00	.35	.01	680.00	2.66	.20	1270.00	4.96	.62	1860.00	7.26	1.24
100.00	.39	.01	690.00	2.69	.20	1280.00	5.00	.63	1870.00	7.30	1.25
110.00	.43	.01	700.00	2.73	.21	1290.00	5.04	.64	1880.00	7.34	1.26
120.00	.47	.01	710.00	2.77	.22	1300.00	5.08	.64	1890.00	7.38	1.27
130.00	.51	.01	720.00	2.81	.22	1310.00	5.12	.65	1900.00	7.42	1.28
140.00	.55	.01	730.00	2.85	.23	1320.00	5.15	.66	1910.00	7.46	1.30
150.00	.59	.01	740.00	2.89	.23	1330.00	5.19	.67	1920.00	7.50	1.31
160.00	.62	.01	750.00	2.93	.24	1340.00	5.23	.68	1930.00	7.54	1.32
170.00	.66	.02	760.00	2.97	.24	1350.00	5.27	.69	1940.00	7.58	1.33
180.00	.70	.02	770.00	3.01	.25	1360.00	5.31	.70	1950.00	7.61	1.35
190.00	.74	.02	780.00	3.05	.26	1370.00	5.35	.71	1960.00	7.65	1.36
200.00	.78	.02	790.00	3.08	.26	1380.00	5.39	.72	1970.00	7.69	1.37
210.00	.82	.02	800.00	3.12	.27	1390.00	5.43	.73	1980.00	7.73	1.38
220.00	.86	.03	810.00	3.16	.27	1400.00	5.47	.74	1990.00	7.77	1.40
230.00	.90	.03	820.00	3.20	.28	1410.00	5.51	.75	2000.00	7.81	1.41
240.00	.94	.03	830.00	3.24	.29	1420.00	5.55	.76	2010.00	7.85	1.42
250.00	.98	.03	840.00	3.28	.29	1430.00	5.58	.77	2020.00	7.89	1.44
260.00	1.02	.04	850.00	3.32	.30	1440.00	5.62	.78	2030.00	7.93	1.45
270.00	1.05	.04	860.00	3.36	.30	1450.00	5.66	.79	2040.00	7.97	1.46
280.00	1.09	.04	870.00	3.40	.31	1460.00	5.70	.80	2050.00	8.01	1.47
290.00	1.13	.04	880.00	3.44	.32	1470.00	5.74	.81	2060.00	8.04	1.49
300.00	1.17	.05	890.00	3.48	.32	1480.00	5.78	.82	2070.00	8.08	1.50
310.00	1.21	.05	900.00	3.51	.33	1490.00	5.82	.83	2080.00	8.12	1.51
320.00	1.25	.05	910.00	3.55	.34	1500.00	5.86	.84	2090.00	8.16	1.53
330.00	1.29	.05	920.00	3.59	.34	1510.00	5.90	.85	2100.00	8.20	1.54
340.00	1.33	.06	930.00	3.63	.35	1520.00	5.94	.86	2110.00	8.24	1.55
350.00	1.37	.06	940.00	3.67	.36	1530.00	5.97	.87	2120.00	8.28	1.57
360.00	1.41	.06	950.00	3.71	.36	1540.00	6.01	.88	2130.00	8.32	1.58
370.00	1.44	.07	960.00	3.75	.37	1550.00	6.05	.89	2140.00	8.36	1.59
380.00	1.48	.07	970.00	3.79	.38	1560.00	6.09	.90	2150.00	8.40	1.61
390.00	1.52	.07	980.00	3.83	.39	1570.00	6.13	.91	2160.00	8.43	1.62
400.00	1.56	.08	990.00	3.87	.39	1580.00	6.17	.92	2170.00	8.47	1.64
410.00	1.60	.08	1000.00	3.90	.40	1590.00	6.21	.93	2180.00	8.51	1.65
420.00	1.64	.08	1010.00	3.94	.41	1600.00	6.25	.94	2190.00	8.55	1.66
430.00	1.68	.09	1020.00	3.98	.41	1610.00	6.29	.95	2200.00	8.59	1.68
440.00	1.72	.09	1030.00	4.02	.42	1620.00	6.33	.96	2210.00	8.63	1.69
450.00	1.76	.09	1040.00	4.06	.43	1630.00	6.37	.97	2220.00	8.67	1.71
460.00	1.80	.10	1050.00	4.10	.44	1640.00	6.40	.98	2230.00	8.71	1.72
470.00	1.84	.10	1060.00	4.14	.44	1650.00	6.44	.99	2240.00	8.75	1.73
480.00	1.87	.11	1070.00	4.18	.45	1660.00	6.48	1.00	2250.00	8.79	1.75
490.00	1.91	.11	1080.00	4.22	.46	1670.00	6.52	1.02	2260.00	8.83	1.76
500.00	1.95	.11	1090.00	4.26	.47	1680.00	6.56	1.03	2270.00	8.86	1.78
510.00	1.99	.12	1100.00	4.30	.48	1690.00	6.60	1.04	2280.00	8.90	1.79
520.00	2.03	.12	1110.00	4.33	.48	1700.00	6.64	1.05	2290.00	8.94	1.80
530.00	2.07	.13	1120.00	4.37	.49	1710.00	6.68	1.06	2300.00	8.98	1.82
540.00	2.11	.13	1130.00	4.41	.50	1720.00	6.72	1.07	2310.00	9.02	1.83
550.00	2.15	.14	1140.00	4.45	.51	1730.00	6.76	1.08	2320.00	9.06	1.85
560.00	2.19	.14	1150.00	4.49	.52	1740.00	6.79	1.09	2330.00	9.10	1.86
570.00	2.23	.14	1160.00	4.53	.52	1750.00	6.83	1.11	2340.00	9.14	1.88
580.00	2.26	.15	1170.00	4.57	.53	1760.00	6.87	1.12	2350.00	9.18	1.89
590.00	2.30	.15	1180.00	4.61	.54	1770.00	6.91	1.13			

Appendix Table 7–12.—Friction loss in trickle irrigation hose, nominal diameter 12 in.

[Inside diameter 12.128 in., discharge increment 20.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
20.00	.08	.00	1160.00	3.22	.23	2300.00	6.39	.90
40.00	.11	.00	1180.00	3.28	.24	2320.00	6.44	.91
60.00	.17	.00	1200.00	3.33	.25	2340.00	6.50	.92
80.00	.22	.00	1220.00	3.39	.25	2360.00	6.55	.94
100.00	.28	.00	1240.00	3.44	.26	2380.00	6.61	.95
120.00	.33	.00	1260.00	3.50	.27	2400.00	6.66	.96
140.00	.39	.01	1280.00	3.55	.28	2420.00	6.72	.98
160.00	.44	.01	1300.00	3.61	.28	2440.00	6.77	.99
180.00	.50	.01	1320.00	3.66	.29	2460.00	6.83	.90
200.00	.56	.01	1340.00	3.72	.30	2480.00	6.88	.92
220.00	.61	.01	1360.00	3.78	.31	2500.00	6.94	.93
240.00	.67	.01	1380.00	3.83	.32	2520.00	7.00	.94
260.00	.72	.02	1400.00	3.89	.32	2540.00	7.05	.96
280.00	.78	.02	1420.00	3.94	.33	2560.00	7.11	.97
300.00	.83	.02	1440.00	4.00	.34	2580.00	7.16	.98
320.00	.89	.02	1460.00	4.05	.35	2600.00	7.22	1.00
340.00	.94	.03	1480.00	4.11	.36	2620.00	7.27	1.01
360.00	1.00	.03	1500.00	4.16	.37	2640.00	7.33	1.03
380.00	1.05	.03	1520.00	4.22	.38	2660.00	7.38	1.04
400.00	1.11	.03	1540.00	4.28	.39	2680.00	7.44	1.06
420.00	1.17	.04	1560.00	4.33	.39	2700.00	7.50	1.07
440.00	1.22	.04	1580.00	4.39	.40	2720.00	7.55	1.08
460.00	1.28	.04	1600.00	4.44	.41	2740.00	7.61	1.10
480.00	1.33	.05	1620.00	4.50	.42	2760.00	7.66	1.11
500.00	1.39	.05	1640.00	4.55	.43	2780.00	7.72	1.13
520.00	1.44	.05	1660.00	4.61	.44	2800.00	7.77	1.14
540.00	1.50	.06	1680.00	4.66	.45	2820.00	7.83	1.16
560.00	1.55	.06	1700.00	4.72	.46	2840.00	7.89	1.17
580.00	1.61	.07	1720.00	4.78	.47	2860.00	7.94	1.19
600.00	1.67	.07	1740.00	4.83	.48	2880.00	8.00	1.20
620.00	1.72	.07	1760.00	4.89	.49	2900.00	8.05	1.22
640.00	1.78	.08	1780.00	4.94	.50	2920.00	8.11	1.23
660.00	1.83	.08	1800.00	5.00	.51	2940.00	8.16	1.25
680.00	1.89	.09	1820.00	5.05	.52	2960.00	8.22	1.27
700.00	1.94	.09	1840.00	5.11	.53	2980.00	8.27	1.28
720.00	2.00	.10	1860.00	5.16	.54	3000.00	8.33	1.30
740.00	2.05	.10	1880.00	5.22	.55	3020.00	8.38	1.31
760.00	2.11	.11	1900.00	5.27	.56	3040.00	8.44	1.33
780.00	2.17	.11	1920.00	5.33	.58	3060.00	8.50	1.34
800.00	2.22	.12	1940.00	5.39	.59	3080.00	8.55	1.36
820.00	2.28	.12	1960.00	5.44	.60	3100.00	8.61	1.38
840.00	2.33	.13	1980.00	5.50	.61	3120.00	8.66	1.39
860.00	2.39	.13	2000.00	5.55	.62	3140.00	8.72	1.41
880.00	2.44	.14	2020.00	5.61	.63	3160.00	8.77	1.43
900.00	2.50	.15	2040.00	5.66	.64	3180.00	8.83	1.44
920.00	2.55	.15	2060.00	5.72	.65	3200.00	8.88	1.46
940.00	2.61	.16	2080.00	5.77	.67	3220.00	8.94	1.48
960.00	2.67	.16	2100.00	5.83	.68	3240.00	8.99	1.49
980.00	2.72	.17	2120.00	5.89	.69	3260.00	9.05	1.51
1000.00	2.78	.18	2140.00	5.94	.70	3280.00	9.11	1.53
1020.00	2.83	.18	2160.00	6.00	.71	3300.00	9.16	1.54
1040.00	2.89	.19	2180.00	6.05	.72	3320.00	9.22	1.56
1060.00	2.94	.20	2200.00	6.11	.74	3340.00	9.27	1.58
1080.00	3.00	.20	2220.00	6.16	.75	3360.00	9.33	1.60
1100.00	3.05	.21	2240.00	6.22	.76	3380.00	9.38	1.61
1120.00	3.11	.22	2260.00	6.27	.77	3400.00	9.44	1.63
1140.00	3.16	.22	2280.00	6.33	.79	3420.00	9.49	1.65

Appendix Table 7-13.—Friction loss in plastic irrigation pipe, nominal diameter 15 in.

[Inside diameter 14.554 in., discharge increment 50.00 gal/min]

Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft	Flow (Q) gal/min	Flow (v) ft/s	Friction loss (J) ft/100 ft
50.00	.10	.00	2650.00	5.11	.43
100.00	.19	.00	2700.00	5.21	.44
150.00	.29	.00	2750.00	5.30	.46
200.00	.39	.00	2800.00	5.40	.47
250.00	.49	.01	2850.00	5.49	.49
300.00	.58	.01	2900.00	5.59	.51
350.00	.67	.01	2950.00	5.69	.52
400.00	.77	.01	3000.00	5.79	.54
450.00	.87	.02	3050.00	5.89	.55
500.00	.96	.02	3100.00	5.99	.57
550.00	1.06	.03	3150.00	6.07	.59
600.00	1.16	.03	3200.00	6.17	.61
650.00	1.25	.03	3250.00	6.27	.62
700.00	1.35	.04	3300.00	6.36	.64
750.00	1.45	.04	3350.00	6.46	.66
800.00	1.54	.05	3400.00	6.55	.68
850.00	1.64	.05	3450.00	6.65	.69
900.00	1.74	.06	3500.00	6.75	.71
950.00	1.83	.07	3550.00	6.84	.73
1000.00	1.93	.07	3600.00	6.94	.75
1050.00	2.02	.08	3650.00	7.04	.77
1100.00	2.12	.08	3700.00	7.13	.79
1150.00	2.22	.09	3750.00	7.23	.81
1200.00	2.31	.10	3800.00	7.33	.83
1250.00	2.41	.11	3850.00	7.42	.85
1300.00	2.51	.12	3900.00	7.52	.87
1350.00	2.60	.13	3950.00	7.61	.89
1400.00	2.70	.13	4000.00	7.71	.91
1450.00	2.80	.14	4050.00	7.81	.93
1500.00	2.89	.15	4100.00	7.90	.95
1550.00	2.99	.16	4150.00	8.00	.97
1600.00	3.08	.17	4200.00	8.10	.99
1650.00	3.19	.18	4250.00	8.19	1.02
1700.00	3.28	.19	4300.00	8.29	1.04
1750.00	3.37	.20	4350.00	8.39	1.06
1800.00	3.47	.21	4400.00	8.49	1.08
1850.00	3.57	.22	4450.00	8.58	1.11
1900.00	3.66	.23	4500.00	8.68	1.13
1950.00	3.76	.25	4550.00	8.77	1.15
2000.00	3.86	.26	4600.00	8.87	1.17
2050.00	3.95	.27	4650.00	8.96	1.20
2100.00	4.05	.28	4700.00	9.06	1.22
2150.00	4.14	.29	4750.00	9.16	1.25
2200.00	4.24	.31	4800.00	9.25	1.27
2250.00	4.34	.32	4850.00	9.35	1.29
2300.00	4.43	.33	4900.00	9.45	1.32
2350.00	4.53	.34	4950.00	9.54	1.34
2400.00	4.63	.36	5000.00	9.64	1.37
2450.00	4.72	.37	5050.00	9.74	1.39
2500.00	4.92	.39	5100.00	9.83	1.42
2550.00	4.92	.40	5150.00	9.93	1.44
2600.00	5.01	.41			

Appendix C—Equations

7–1 $$P_w = \frac{eS_eS_w}{S_pS_r} \times 100$$

7–2 $$P_w = \frac{eS_e'(S_e' + S_w)}{2(S_pS_r)} \times 100$$

7–3 $$P_w = \frac{e[A_s + (\tfrac{1}{2}S_e' \times PS)]}{(S_pS_r)} \times 100$$

7–4 $$F_{mn} = (M_{ad})(WHC)(RZD)(P_w)$$

7–5 $$T_d = u_d[P_s + 0.15(1.0 - P_s)]$$

7–6 $$F_n = T_dI_f$$

7–7 $$EU = 100(1.0 - \frac{1.27}{\sqrt{e}}v)\frac{q_n}{q_a}$$

7–8a $$F_g = \frac{F_nT_r}{EU}$$

7–8b $$F_g = \frac{F_n}{EU(1.0 - LR_t)}$$

7–9 $$F_{(gp/d)} = 0.623\frac{S_pS_rF_g}{I_f}$$

7–10 $$F_{(an)} = (U - R_e - W_s)[P_s + 0.15(1.0 - P_s)]$$

7–11 $$E_s = EU$$

7–12 $$E_s = \frac{EU}{T_R(1.0 - LR_t)}$$

7–13 $$F_{sg} = \frac{F_{an}}{E_s(1.0 - LR_t)}$$

7–14 $$V_i = \frac{F_{an}A}{12(1.0 - LR_t)E_s/100}$$

7–15 $$Y = \frac{EC_w - \min EC_e}{\max EC_e - \min EC_e} \times 100$$

7–16 $$LR_t = \frac{L_n}{F_n} = \frac{L_N}{F_{an}} = \frac{EC_w}{EC_{dw}}$$

7–17 $$LR_t = \frac{EC_w}{2(\max EC_e)}$$

7–18 $$v = \frac{S}{\bar{q}} = \frac{\sqrt{q_1^2 + q_2^2 \ldots + q_n^2 - n(\bar{q})^2/\sqrt{n-1}}}{\bar{q}}$$

7–19 $$v_s = \frac{v}{\sqrt{e'}}$$

7–20 $$q = k_dh^x$$

7–21 $$x = \frac{\log(q_1/q_2)}{\log(h_1/h_2)}$$

7–22 $$l_c = \frac{hgd^4\pi}{98.6q\nu}$$

7–23 $$q = 187ac_q\sqrt{2gh}$$

7–24 $$q = 187ac_q\sqrt{2g(h - h^1)}$$

7–25 $$h^1 = \frac{h}{1 + m^2}$$

7–26 $$q = 187ac_q\sqrt{2g}\ h^{0.4}$$

7–27 $$q = 187ac_q\sqrt{2g}\ h^x$$

7–28 $$q = 187ac_q\sqrt{2g}(h/m')^{0.7}$$

7–29 $$q = 187ac_q\sqrt{2gh/m'}$$

7–30 $$T_a = \frac{F_{(gp/d)}}{eq_a}$$

7–31 $$h_a = (\frac{q_a}{k_d})^{1/x}$$

7–32 $$EU = 100\ q_n'/q_a'$$

7–33a $$EU = 100(1.0 - 1.27\frac{v}{\sqrt{e'}})\frac{q_n}{q_a}$$

7–33b $$EU = 100(1.0 - 1.27v_s)\frac{q_n}{q_a}$$

7–34 $$\triangle H_s = 2.5(h_a - h_n)$$

7–35a $$Q_s = 726\frac{A}{N}\frac{eq_a}{S_pS_r}$$

7–35b $$Q_s = 726\frac{A}{N}\frac{q_a}{S_eS_l}$$

7–36 $$Q_s = 726\frac{A}{N}\frac{e}{S_p}q_a$$

7–37 $Q_t = 5{,}430 \frac{V_i}{Q_s}$

7–38 $q_n = q_a \left(\frac{h_n}{h_a}\right)^x$

7–39 $h_n = (H_m - \triangle H_m - \triangle h)$

7–40 $F_n = 1.604 \frac{EU}{100} \frac{eq_a}{S_p S_r}$

7–41 $q_f = \frac{F_r A}{H F_c H_r}$

7–42 $C_t = \frac{F_r A}{F_c}$

7–43 $q_c = \frac{0.006 C Q_s}{csg}$

7–44 $J = \frac{h_f 100}{L} = 1{,}050 \frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}}$

7–45 $N_R = 3{,}214 \frac{Q}{D}$

7–46 $h_f = f \frac{L}{D} \frac{v^2}{2g}$

7–47a $f = \frac{64}{N_R}$

7–47b $\frac{1}{\sqrt{f}} = 0.80 + 2.0 \log (N_R \sqrt{f})$

7–48 $f = 0.32\, N_R^{-0.25}$

7–49a $J = \frac{h_f 100}{L} = 0.133 \frac{Q^{1.75}}{D^{4.75}}$

7–49b $J = \frac{h_f 100}{L} = 0.100 \frac{Q^{1.83}}{D^{4.83}}$

7–50 $h_e = K_f \frac{V^2}{2g}$

7–51a $l' = l\left(\frac{S_e + f_e}{S_e}\right)$

7–51b $J' = J \left(\frac{S_e + f_e}{S_e}\right)$

7–52 $h_f = J'FL/100$

7–53 $\frac{h_{fx}}{L/100} = J'F\left(\frac{x}{L}\right)^{2.75}$

7–54 $PW(r) = \left[\frac{(1+r)^n - (1+i)^n}{(1+r) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right]$

7–55 $EAE(r) = \left[\frac{(1+r)^n - (1+i)^n}{(1+r) - (1+i)}\right] \times \left[\frac{i}{(1+i)^n - 1}\right]$

7–56 $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$

7–57 $C_{whp} = \frac{(Q_t)(P_{uc})[EAE(r)]}{(E_p)(BHP/P_u)}$

7–58 $A_f = \frac{0.001 C_{whp}}{(CRF)(P_c)}$

7–59 $Q_s' = A_f Q_s$

7–60 $(H_{fe})_m = \sum_1^m h_f \pm \triangle El$

7–61 $L_s = \frac{\triangle H}{J_s - J_l} \times 100$

7–62 $q_l = \frac{l}{S_e} \frac{q_a}{60} = \frac{n_e q_a}{60}$

7–63a $h_l = h_a + 0.75 h_{fp}[z^{3.75} + (1 - z)^{3.75}] - \frac{\triangle El}{2}(2z - 1)$

7–63b $h_l = h_a + 0.75 h_{fp} (0.5)^{2.75} = h_a + 0.11 h_{fp}$

7–63c $h_l = h_a + \frac{3h_f}{4} + \frac{\triangle El}{2}$

7–64a $h_c = h_a - \left(\frac{h_f}{4} + \frac{\triangle El}{2}\right)$

7–64b $h_c = h_l - (h_f + \triangle El)$

7-65a $(h_f)_b \cong (h_f)_a(\frac{l_b}{l_a})^{2.75}$

7-65b $l_b \cong l_a (\frac{(h_f)_b}{(h_f)_a})^{1/2.75}$

7-66 $\triangle h = \frac{J'F}{10} \frac{L}{100} (\frac{\triangle h}{L/100})'$

7-67 $Y = (S/J')^{1/1.75}$

7-68 $S' = SY - J'F(Y)^{2.75}$

7-69 $\frac{S - S'}{J'F} = (x/L)^{2.75} - (1 - x/L)^{2.75}$

7-70 $\triangle h = \frac{L}{100} [J'F(x/L)^{2.75} + S' - S(x/L)]$

7-71a $\triangle h_c = S'(L/100)$

7-71b $\triangle h_c = S^{1.57}(J')^{-0.57}(1 - F)L/100$

7-72 $\triangle h = \frac{L}{100} (J'F + S' - S)$

7-73 $(\triangle H_m)_a = \triangle H_s - \triangle h'$

7-74 $L_p = [(n_r)_p - 1]S_r$

7-75 $L_m = (n_r - 1/2)S_r$

7-76a $H_m = h_l + \triangle H'_m$

7-76b $H_m = h_a + \triangle h' + \triangle H'_m$

7-77 $Q'_s = A_f q_m$

7-78 $L_d = \frac{q_d - q_{d-1}}{q_m} L_m$

7-79a $k = (L_m/q_m)(0.1 \text{ gpm/ft})$

7-79b $k = (S_l/q_l)(0.1 \text{ gpm/ft})$

7-80 $H_f = k(H_{fg})$

7-81a $\triangle H_m = H_f$

7-81b $\triangle H_m = H_f + S(L_m/100)$

7-81c $\triangle H_m = H_f - [S(0.1 - \frac{0.36}{c}) \frac{L_m}{100}]$

7-82a $Q''_s = \frac{H_f}{(\triangle H_m)_a} Q'_s$

7-82b $Q''_s = \frac{H_f}{(\triangle H_m)_a - S(L_m/100)}$

7-82c $Q''_s = \frac{H_f}{(\triangle H_m)_a + [S(1.0 - \frac{0.36}{c})L_m/100]}$

7-83 $S_f = \frac{(q_l)_c}{(q_l)_a} = \frac{(n_p)_c}{(n_p)_a}$

7-84 $H_f = JFF_s(L_m/100) = JF'(L_m/100)$

7-85 $J = J_x(\frac{q_m}{q_x})^{1.8}$

7-86 $j = \frac{(\triangle H_m)_a}{L_m/100}$

7-87 $j' = \frac{(\triangle H_m)_a}{k}$

7-88 $S' = \frac{SL_m}{100k} = \frac{Sq_m}{10} = \frac{\triangle El}{k}$

7-89 $(H_f)_2 = \frac{L_2}{L_1} \frac{(F_s)_2}{(F_s)_1} (\frac{q_2}{q_1})^{1.8} (H_f)_1$

7-90 $F'_{aw} = \frac{1.604eq'_aT_a}{A_w}$

7-91 $F'_a = \frac{1.604eq'_aT_a}{S_p \times S_r}$

7-92 $F'_{(gp/d)} = \frac{eq'_aT_a}{I_f}$

7-93 $EU'_m = 100\ q'_n/q'_a$

7-94a $ERF = \frac{\text{average MLIP} + (1.5 \text{ minimum MLIP})}{2.5(\text{average MLIP})}$

7-94b $ERF = (\frac{\text{minimum MLIP}}{\text{average MLIP}})^x$

7-95 $EU' = (ERF)(EU'_m)$

7-96 $F_n = (F'_n - R'_e)[\frac{P_s}{100} + 0.15(1.0 - \frac{P_s}{100})]$

7-97a $PE_{lq} = \frac{EU'}{T_r(1.0 - LR_t)}$

7-97b $PE_{lq} = EU'$

7-98 $E_{lq} = \frac{100G}{F'_{(gp/d)}}$

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Section 15

IRRIGATION

Chapter 8

IRRIGATION PUMPING PLANTS

Soil Conservation Service
United States Department of Agriculture

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15 IRRIGATION

CHAPTER 8 - IRRIGATION PUMPING PLANTS

CONTENTS

	Page
General	8-1
Centrifugal pumps	8-2
General	8-2
Operation	8-2
Characteristics	8-2
Characteristic curves	8-6
Data for selecting pump	8-6
Installation	8-8
Priming	8-11
Trouble Checklist	8-16
Pump fails to prime	8-16
Pump fails to develop sufficient pressure or capacity	8-17
Pump takes too much power	8-18
Pump leaks excessively at stuffing box	8-19
Pump is noisy	8-19
Deep-Well Turbine Pumps	8-19
General	8-19
Operation	8-19
Characteristic curves	8-21
Pump selection	8-23
Data for selecting pump	8-23
Installation	8-25
Submersible Pumps	8-25
General	8-25
Operation	8-27
Installation	8-27
Propeller Pumps	8-29
General	8-29
Axial flow	8-29
Mixed flow	8-29
Operating characteristics	8-29
Characteristic curves	8-31
Installation	8-34
Data for selecting pump	8-34

CONTENTS--Cont'd

	Page
Determining Operating Conditions	8-35
General	8-35
Determining head for centrifugal pumps	8-35
Determining head for deep-well turbine pumps	8-38
Determining head for propeller pumps	8-38
Drives	8-41
General	8-41
Direct drive	8-41
Belt drive	8-43
90° gear heads	8-43
Power takeoff	8-47
Cavitation	8-47
Booster pumps	8-51
Power for pumping	8-52
General	8-52
Electric motors	8-52
Stationary internal combustion engines	8-55
Tractor power	8-58
Power Requirements	8-59
General	8-59
Power requirements for electric motors	8-60
Power requirements for internal combustion engines	8-61
Cost of Pumping	8-62
General	8-62
Fixed costs	8-63
Operating costs	8-64
Summary	8-68

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 8 - IRRIGATION PUMPING PLANTS

FIGURES

Figure		Page
8-1	Horizontal centrifugal pump for surface or pit installation	8-3
8-2	Effect of speed change on centrifugal pump performance	8-5
8-3	Typical characteristic curve for horizontal centrifugal pump	8-7
8-4	Suggestions for installing centrifugal pumps	8-9
8-5	Priming with foot valve and water supply	8-12
8-6	Priming with foot valve and hand primer	8-12
8-7	Priming with exhaust primer	8-14
8-8	Priming with manifold primer	8-14
8-9	Priming by dry vacuum pump	8-15
8-10	Self-priming centrifugal pumps	8-15
8-11	Deep-well turbine pump	8-20
8-12	A, Typical characteristic curves for deep-well turbine pump operating at constant speed. B, Heads at which a typical 10-inch turbine pump will deliver 500 g.p.m. together with related factors of pump	8-22
8-13	Effect of change in operating conditions on pump efficiency	8-24
8-14	Deep-well turbine pump installation	8-26
8-15	Submersible pump	8-28
8-16	Propeller pumps	8-30
8-17	Clearance required for propeller pump	8-32
8-18	Typical characteristic curves for an 18-inch axial-flow single-stage propeller pump with three different type propellers	8-33
8-19	Example of determining head for centrifugal pumps	8-36
8-20	Example of determining head for turbine pumps	8-39
8-21	Example of determining head for propeller pumps	8-40
8-22	Examples of direct drive	8-42
8-23	Examples of flat-belt drive	8-44
8-24	Rules for determining size and speed of pulleys, sheaves, gears, or sprocket wheels	8-45
8-25	Examples of V-belt drives	8-46
8-26	Examples of right-angle gear head drives	8-48
8-27	Examples of power-takeoff drives	8-48
8-28	Correct and incorrect power-takeoff shaft alinement	8-49
8-29	Horsepower output of an internal combustion engine	8-56

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 8 - IRRIGATION PUMPING PLANTS

TABLES

Table		Page
8-1	Maximum design static siphon lift in feet	8-37
8-2	Efficiencies of electric motors operating at full speed	8-61
8-3	Pumping plant depreciation	8-64
8-4	Electric motor power costs	8-67

SECTION 15

IRRIGATION

CHAPTER 8. IRRIGATION PUMPING PLANTS

General

The pumping plant is essential in many irrigation systems. Pumping conditions usually determine the type of pump that should be used. The irrigation pump must be fitted to the water supply and to the job to be accomplished if high efficiencies are to be obtained. Its selection must be accurately made to secure desired results and economical operation.

Several different types of pumps are available to meet the needs of irrigation. These include the centrifugal, turbine, propeller airlift and piston or reciprocating pumps. The centrifugal, turbine, and propeller pumps are the types commonly used for irrigation pumping.

Centrifugal pumps usually give efficient operation over a relatively wide range of operating conditions when pumping against total heads exceeding approximately 12 feet. The centrifugal pump sucks the water from the source of supply to the pump. It is, therefore, limited to locations and conditions where this distance is within the limits of suction. This limitation will be discussed under the section on determining suction lifts for centrifugal pumps.

Because it operates successfully under any head, the deep-well turbine pump is best adapted to use in wells. It is used in installations where centrifugal pumps cannot be set near the water surface.

The propeller pump is adapted to delivering a large quantity of water under low heads. It is adapted to surface irrigation where large streams at low heads are required. The propeller pump also is used extensively in pumping for drainage.

For deep wells with relatively high static water levels, the airlift pump is of limited application. The initial cost is generally lower than that for other types of pumps, but the operating efficiencies are rather low.

The piston or reciprocating pump is no longer used extensively in irrigation. This pump is efficient for relatively small capacities at high heads.

Centrifugal Pumps

General.

Centrifugal pumps are built in two types--the horizontal centrifugal and the vertical centrifugal. The horizontal type has a vertical impeller connected to a horizontal shaft. The vertical centrifugal pump has a horizontal impeller connected to a vertical shaft.

Both types of centrifugal pumps draw water into their impellers, so they must be set only a relatively few feet above the water surface. In this respect the vertical type has an advantage in that it can be lowered to the depth required to pump water and the vertical shaft extended to the surface where power is applied. The centrifugal pump is limited to pumping from reservoirs, lakes, streams, and shallow wells where the total suction lift is not more than approximately 20 feet.

The horizontal centrifugal (fig. 8-1) is the one most commonly used in irrigation. It costs less, is easier to install, and is more accessible for inspection and maintenance; however, it requires more space than the vertical type. To keep the suction lift within operating limits, the horizontal type can be installed in a pit but it usually is not feasible to construct watertight pits more than about 10 or 15 feet deep. Electrically driven pumps are best for use in pits because they require the least cross-sectional area.

The vertical centrifugal pump may be submerged or exposed. The exposed pump is set in a watertight sump at an elevation that will accommodate the suction lift. The submerged pump is set so the impeller and suction entrance are under water at all times. Thus, it does not require priming. But maintenance costs may be high as it is not possible to give the shaft bearings the best attention. Pumps of this kind usually are restricted to pumping heads of about 50 feet.

Operation.

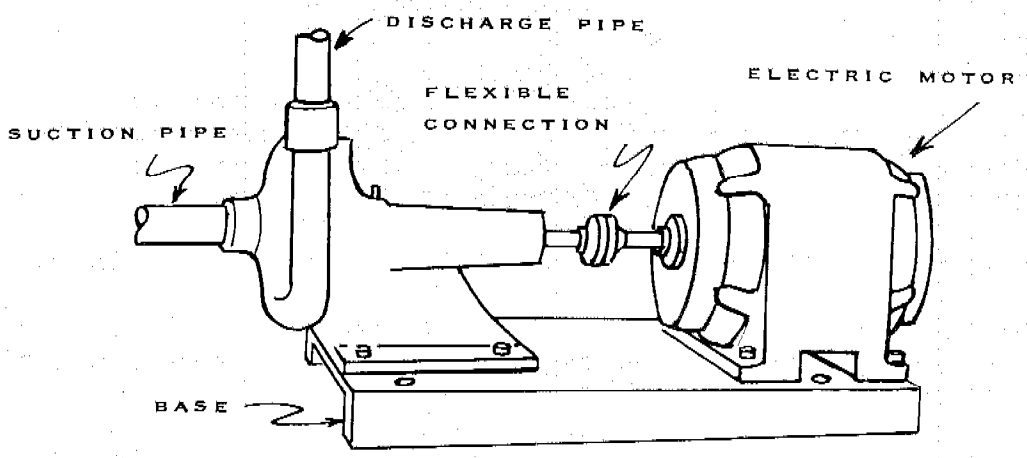
The centrifugal pump operates on the principle of centrifugal action. In a centrifugal pump, a motor or other driver rotates an impeller fitted with vanes immersed in water and enclosed in a casing. Water enters the case at the center and is immediately engaged by the impeller which is in rapid rotation. This rotation causes a flow from the center of the impeller to its rim or the outside of the case where pressure head is rapidly built up. To relieve this pressure, the water escapes through the discharge pipe. The centrifugal pump will not operate until the case is entirely full of water or primed. The need of priming is one of the disadvantages of the horizontal centrifugal pump.

Characteristics.

The principal characteristics of a centrifugal pump are:

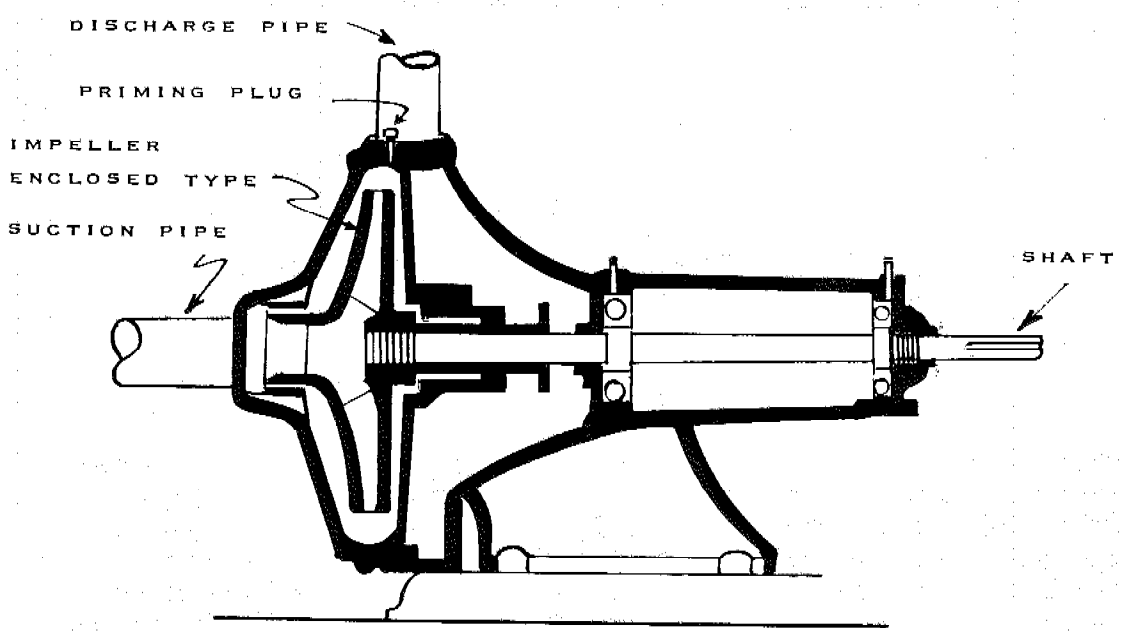
1. Smooth, even flow--easy on pump, motor, piping, and foundation.

2. Adapted to high-speed operation and to different speeds.



DIRECT CONNECTED HORIZONTAL CENTRIFUGAL PUMP

INTERNAL COMBUSTION OR ELECTRIC MOTOR MAY BE USED



CROSS SECTION OF MODERN HORIZONTAL CENTRIFUGAL PUMP

SINGLE SUCTION ENCLOSED IMPELLER

Figure 8-1.--Horizontal centrifugal pump for surface or pit installation.

3. Nonoverloading of power unit with increased heads but there may be some danger of overloading if head is decreased.

4. Capacity and head depend upon r.p.m. and impeller diameter and width. In a given pump, the capacity and head will vary according to the individual operating characteristics of that pump; that is, an increase in head reduces the capacity and vice versa.

5. Horsepower is a function of capacity, head, and pump efficiency.

6. When the speed is kept constant, capacity decreases as head increases and power is reduced. Likewise, when the head is reduced, capacity increases and power goes up.

7. When the operating speed is changed (fig. 8-2) the capacity will change in direct proportion to the variation in speed. At the same time, the head will vary as a square of the change in speed while horsepower will change as the cube of the change in speed. This is represented by the following formula (variable speed-diameter constant):

$$\frac{\text{r. p. m.}_1}{\text{r. p. m.}_2} = \frac{\text{cap.}_1}{\text{cap.}_2} = \frac{\sqrt{\text{head}_1}}{\sqrt{\text{head}_2}} = \frac{\sqrt[3]{\text{hp}_1}}{\sqrt[3]{\text{hp}_2}}$$

8. When it is necessary to vary the characteristics of a pump operating at constant speed, the same relationships expressed in 6 hold except that here it is the diameter of the impeller that is changed. Then the capacity varies directly with the diameter; the head varies as a square of the diameter; and the horsepower varies as a cube of the diameter. This is expressed by the following formula (variable diameter-constant speed):

$$\frac{\text{dia.}_1}{\text{dia.}_2} = \frac{\text{cap.}_1}{\text{cap.}_2} = \frac{\sqrt{\text{head}_1}}{\sqrt{\text{head}_2}} = \frac{\sqrt[3]{\text{hp}_1}}{\sqrt[3]{\text{hp}_2}}$$

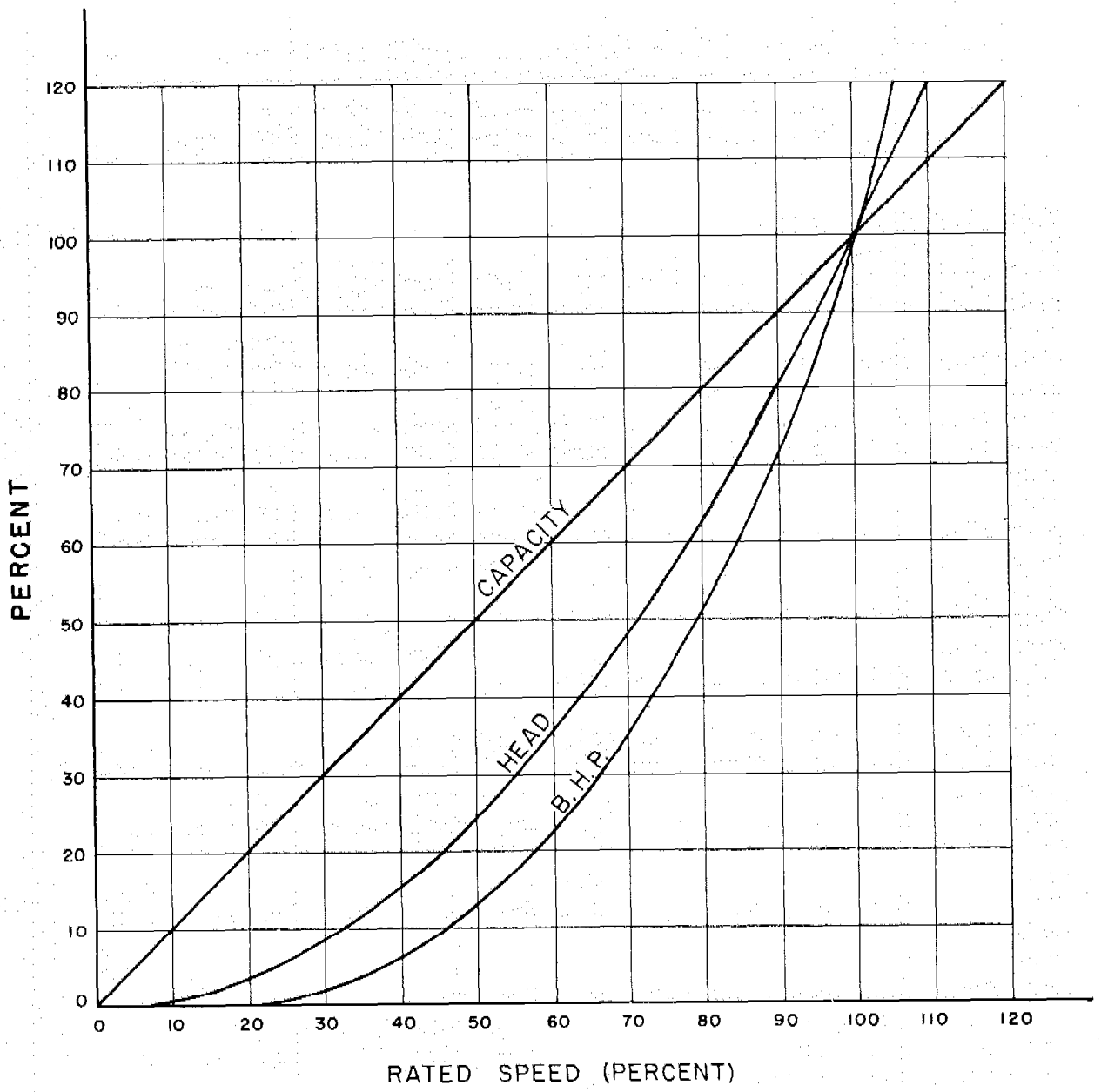


Figure 8-2.--Effect of speed change on centrifugal pump performance.

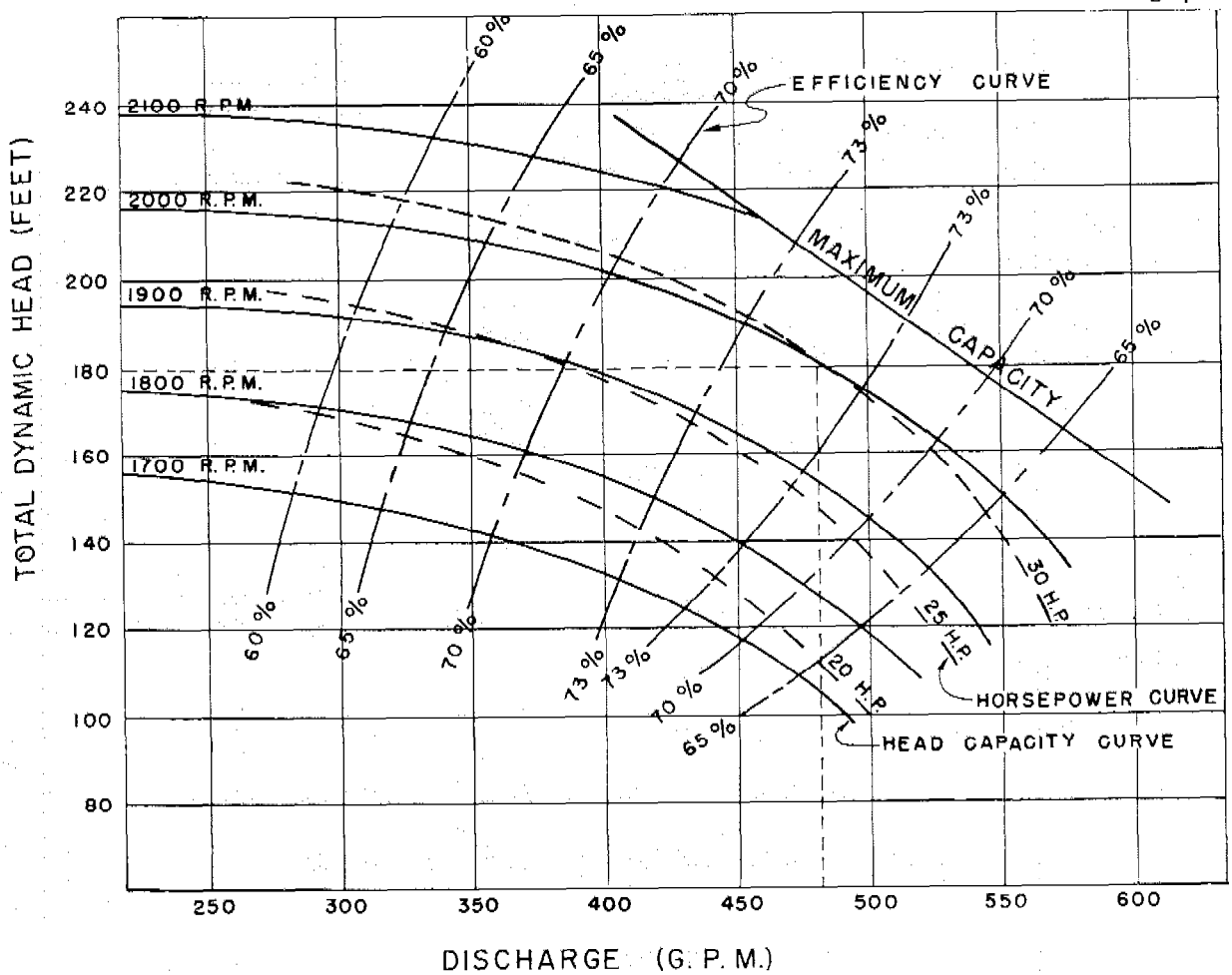
9. These changes (7 and 8) take place with little or no change in efficiency for small changes in speed and impeller diameter (maximum increase of speeds of about 5 percent). For large changes in speed or impeller diameter, the efficiency will be reduced.

Characteristic Curves.
For a particular job, the best selection of a pump will be one that will operate at its peak efficiency. Unfortunately, this is rarely possible for there is only one capacity and one head condition for each pump where the highest efficiency is obtained. Because it is obviously impossible for any manufacturer to design and build the many pumps required to meet all operating conditions, manufacturers have settled upon standard designs for required head and capacity ranges. A well-designed and integrated line of pumps will be so arranged that it is possible to select some pump from the line for any condition and obtain an efficiency that is within a few percentage points of the maximum. Characteristic curves are available and should be used to select the best pump for the particular job.

These curves have been developed at the factory after exhaustive tests during which the water capacity, pressure, power input, etc., are carefully measured and plotted on a curve.

A full set of characteristic curves includes, in addition to the head-capacity curve for different speeds, an efficiency curve and a horsepower curve (fig. 8-3). The head-capacity curve for the constant speed of the pump represents the varying quantities of water delivered by the pump with variations in head. Head-capacity curves for different recommended speeds of the pump are shown. The horsepower curve shows the amount of power required to drive the pump. The efficiency curve shows the amount of usable work done by the pump in percent of power delivered to the pump shaft. Efficiencies may be determined for any given head, speed, and capacity. The pump selected should be within the range of greatest efficiency. Pumps of identical design will have practically identical characteristics with only slight differences due to unavoidable foundry variations.

Data for Selecting Pump.
The following information usually is needed by the pump manufacturer to furnish the correct size and type of pump for a particular installation:



EXAMPLE IN USE OF CURVE-

Required:

A pump and power unit capable of delivering 480 g.p.m. at 180' of head.

Solution:

It is important to choose a pump that will operate near its highest efficiency most of the time. The pump represented by the above curve will satisfy this condition. Find 180' of t. d. h. on the left side of curve, follow the dotted line to its intersection with the 480 g.p.m. line extending up from the bottom. The intersection of the vertical and horizontal dotted lines indicates that this pump will be satisfactory if operated at 2000 r. p.m. It will then operate at its highest efficiency of 73 percent and will require a power unit capable of producing 30 h.p. or greater to the pump shaft at 2000 r. p. m.

Figure 8-3.--Typical characteristic curve for horizontal centrifugal pump.

Source of water supply . . . . . _____
Vertical suction lift . . . . . _____ft.
Length of suction pipe . . . . . _____ft.
Number and kinds of bends required . . . . . _____
Foot valve and strainer. . . . . _____
Static discharge lift . . . . . _____ft.
Discharge head required . . . . . _____ft.
Discharge capacity of pump . . . . . _____g.p.m.
Pump location: Movable_____ Permanent _____
Type of driver: Electric _____Voltage_____Phase_____Cycle_____
Gasoline _____Diesel_____
Power Takeoff_____Natural or L.P. gas_____
Power unit: Separate from pump_____Combined with pump_____

Installation.
For a centrifugal pump to continue to operate at its designed efficiency and also to prolong the life of the equipment, the pump should be correctly located, have a good foundation, and be properly alined. The following factors should be considered in locating the pump:

1. Easily accessible both for inspection and maintenance.

2. Covered to protect it from the elements. A house can be used on permanent installations. In the case of a house, available headroom should be provided for servicing the equipment.

3. Safeguarded against flood conditions unless a wet pit-type pump is used.

4. Placed as close as possible to the water supply so as to make the suction line short and direct.

Pumping units that are to be installed in a permanent location provide the opportunity for developing the best type of foundation (fig. 8-4). Concrete is the best material for constructing a good pump foundation. The pump unit should be securely fastened to the foundation. A recommended method of setting the foundation bolt is shown. The coupling between the pump and power unit must be in correct alinement regardless of the type of coupling. Figure 8-4 shows how a coupling can be checked for alinement with a steel straightedge. When the coupling is by a shaft and double universal joint, a shield should be placed over and around the two horizontal sides to protect the operator from the fast-moving shaft.

To operate properly, the pump must be at a level position at all times. Figure 8-4 shows how 4 to 6 wedges can be used to raise the entire pumping unit about 3/4-inch above the foundation. The wedges can then be adjusted as necessary to bring the pump into a level position. After the pump has been leveled, a dam should be built at least 2-1/2 inches high around the base plate; then concrete poured in to required depth and allowed to harden thoroughly. The wedges may be left in place. When the concrete is hardened, the foundation bolt should be tightened

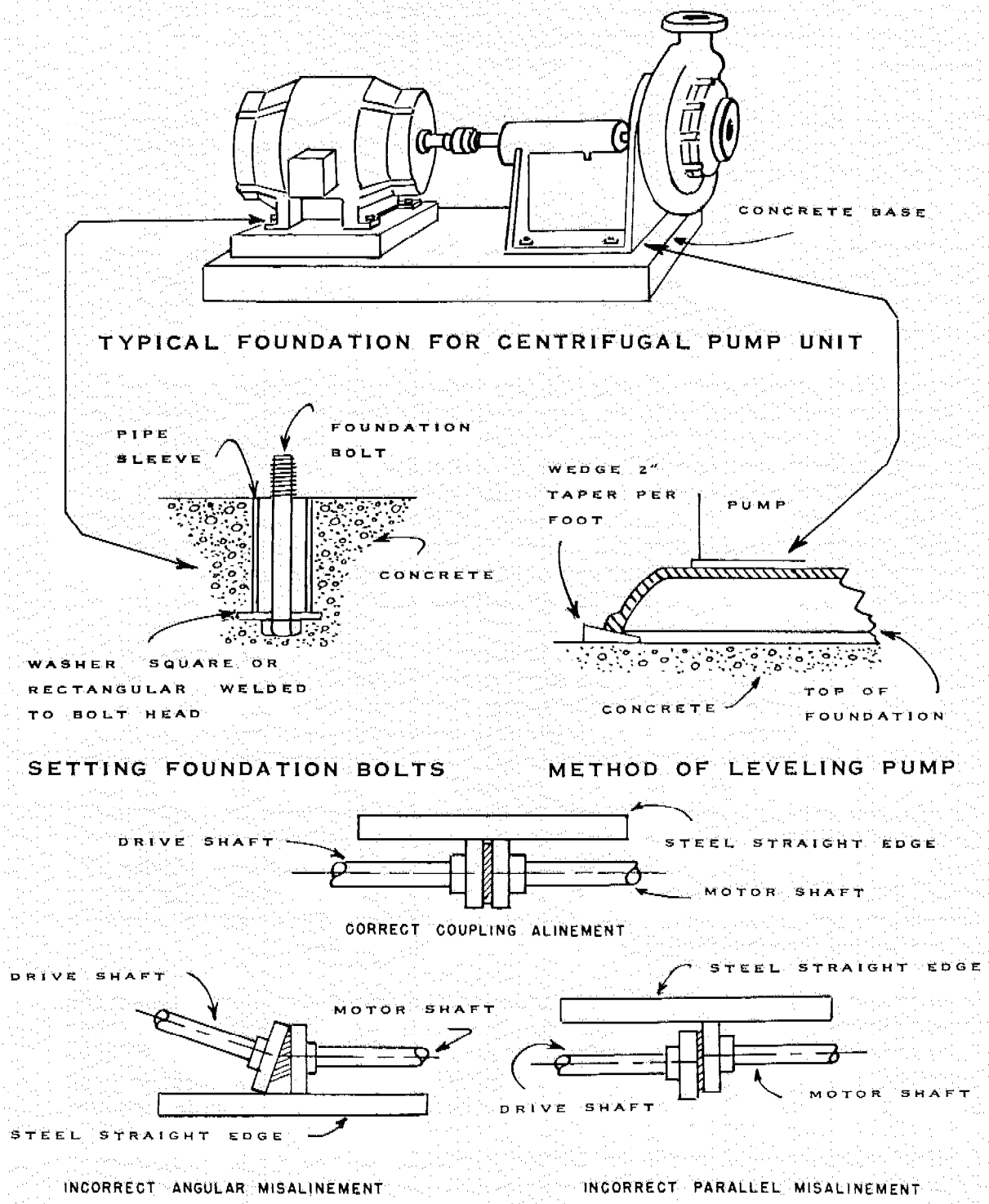


Figure 8-4.--Suggestions for installing centrifugal pumps.

and a recheck made of the alinement. If there is any misalinement, it can be corrected by placing shims under the pump, motor, or brackets.

The motor should now be checked to see that it rotates in the proper direction. The rotation of the motor must be in the same direction as the arrows on the pump casing.

It is important that pumps line up naturally with their power unit and piping. Pipes should not be forced into place with flange bolts as this may draw the pump out of alinement. Suction and discharge pipelines should be supported independently of the pump so as not to put any strain on the pump casing.

The suction pipe, particularly in the case of long intake pipes and high suction lifts, should be laid with a uniform slope, upward from the source of water to the pump. There should be no high spots where air can collect and cause the pump to lose its prime. The inlet end of the suction pipe should be suspended above the earth bottom of a stream or pond or laid in a sump made of concrete or metal. On horizontal suction lines where a reducer is used, it should be of the eccentric type with the straight section on the upper side of the line and the tapered section on the bottom side.

Air may enter the suction pipe entrained in the water, or by means of whirlpools which form in the sump when the water velocity is too high in the intake pipe. If the water level in the sump is too low, or the inlet nozzle is not sufficiently submerged, air may enter the suction pipe through vortex or whirlpool. This generally can be overcome by using a larger suction pipe, especially if the pipe is flared. In shallow water, a mat or float located above the suction inlet will reduce the vortex. Pipe sizes should be increased until the water velocity is less than 3 feet per second at the entrance. A stream of water falling into the sump near the intake pipe will churn air into the water and cause trouble in the suction line. This can be overcome by extending the suction line deeper into the water.

When water must be pumped from a well or a sump of small cross-sectional area, the water will tend to rotate, and this will interfere with the flow into the suction line. This is particularly true in cylindrical sumps or wells. A baffle placed on opposite sides of the suction pipe and at right angle to the rotation of the water overcomes this trouble.

A short elbow should never be bolted directly to the suction opening of a pump. Such a sharp bend so near the pump inlet causes a disturbance in the waterflow and may result in noisy operation, loss of efficiency, and heavy end thrusts. This is particularly true when the suction lift is high. If it is necessary to make a bend in the suction line, it should be in the form of a long sweep or long radius elbow and should be placed as far away from the pump as is practicable.

Screens or strainers should be used to exclude debris from the suction line. If the source of water contains large amounts of small debris, a screen placed around and 2 or 3 feet from the inlet of the suction hose will provide good protection and be less likely to clog. Strainers are generally small and are fastened to the end of the suction pipe. They are satisfactory in relatively clear water.

In some cases, it is not possible to locate the centrifugal irrigation pump in a permanent location. It may be needed in more than one location on the farm. This increases the difficulty of providing a proper foundation. Portable pump units generally are mounted on wheels or skids. It is highly important to locate this type unit so that it is level, is on firm ground, and is securely staked in place so that it will not shift during the time it is operating.

In pumping from rivers with moderately sloping banks, the horizontal centrifugal pump may be mounted on skids, on sloping timbers or track so that it can be removed quickly from floods. This method also can be used where the water level fluctuates sufficiently to be out of range of suction lift if the pump were installed in a permanent location. With steep banks it may be necessary to build a foundation platform secured to piling or to place the pump unit on a floating barge or boat.

Priming.

Centrifugal pumps, due to their nonpositive action, must be primed before the pump will operate. They will not lift water from a source of supply unless the pump casing and the suction pipe are both full of water. This can be accomplished by one of the following priming methods that are generally used in irrigation pumping:

1. By use of a foot valve and water from an outside supply (fig. 8-5). The outside supply must be large enough to keep the pump and suction line filled until the pump is primed. To prime, close discharge gate valve, open air vent valve, and open gate valve in supply line until all air is expelled and water issues from vent openings. Close valve in supply line, close air vent valves, and start pump; then open discharge gate valve.

2. By separate hand-controlled priming pump and foot valve (fig. 8-6). The hand-priming pump is a simple, high-speed air pump with its primer suction inlet connected to the priming part of the centrifugal pump. If connection is made on the pump discharge, a valve must be installed in the priming line. The pump handle is used to actuate a diaphragm in the priming-pump chamber. Air is drawn into the chamber from the centrifugal pump through a suction valve on the "upstroke" and discharged through a discharge valve on the "downstroke." To prime the pump, close the discharge gate valve and air vent valve. Open valve in priming line. Exhaust air from pump and suction piping until water flows from priming pump. Close valve in priming line, start centrifugal pump, and open discharge gate valve.

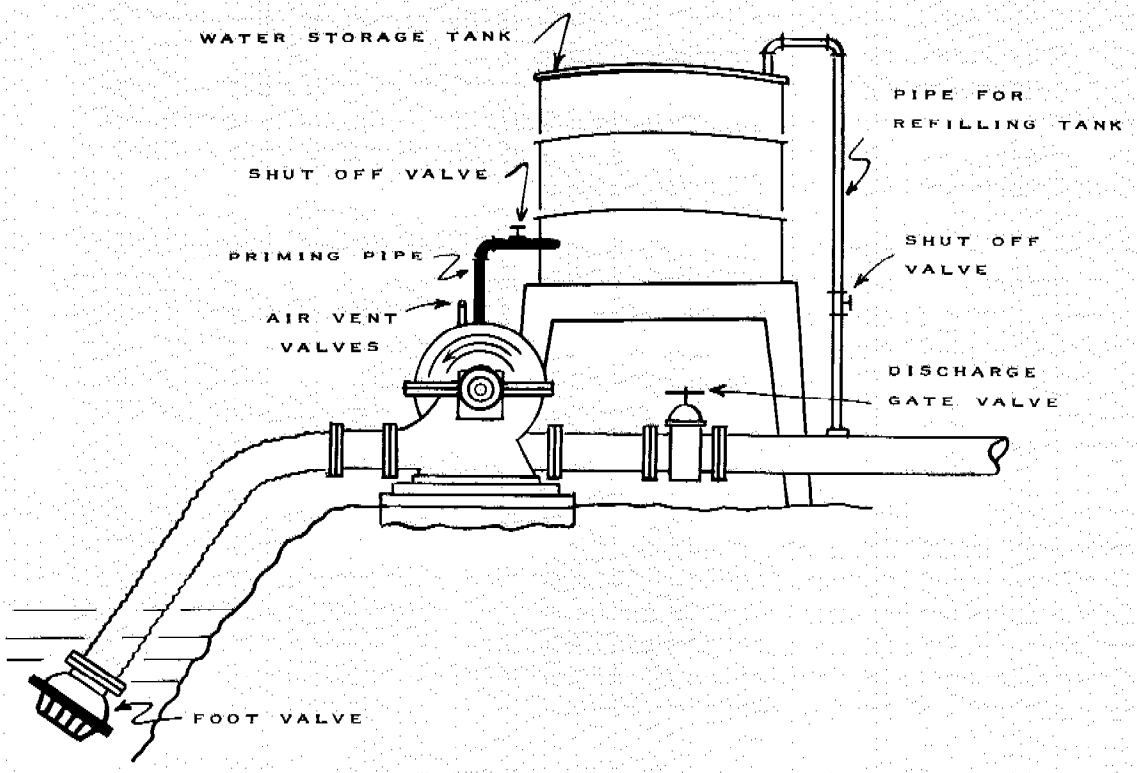


Figure 8-5.--Priming with foot valve and water supply.

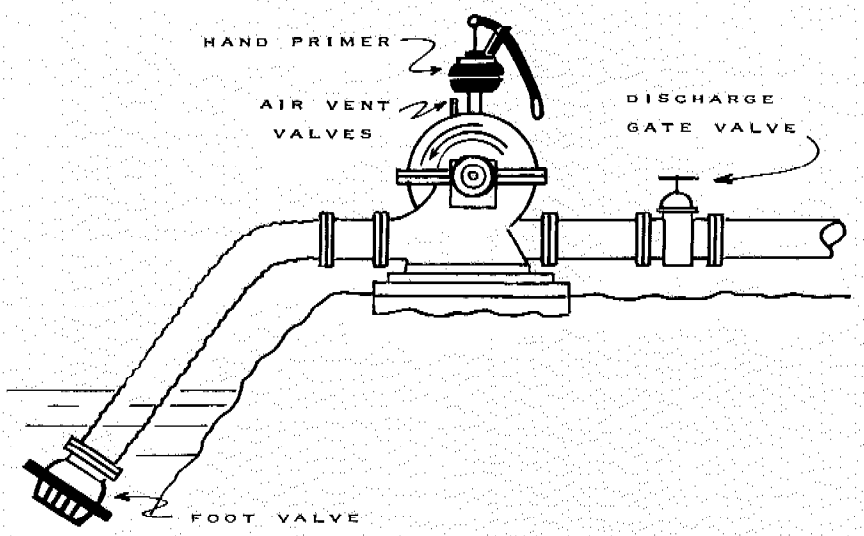


Figure 8-6.--Priming with foot valve and hand primer.

3. By engine exhaust (fig. 8-7). Pumps powered by combustion engines can be primed by a device utilizing the engine's exhaust gas. It is known as an ejector primer. This device is essentially a velocity pump for the removal of air from the centrifugal pump and the suction line by the entraining action of a rapidly moving jet of exhaust gas from the engine. With the ejector primer, a check valve or gate valve is used on the discharge side of the pump to prevent the entrance of additional air into the pump casing during priming. A small tube with a shutoff valve connects the ejector to the pump casing, forming a passageway for air removal.

   To prime the pump, close the discharge gate valve, open the shutoff valve, and start the engine. Hold the handle of the primer down on the exhaust valve to close it. Exhaust gas is now bypassed through the ejector. The rapidly moving exhaust gas expanding and contracting in passing through the ejector nozzle and Venturi tube entrains air in the mixture at the induction chamber. The continued entraining effect rapidly removes air from the pump casing, and water is drawn into the suction pipe and pump casing.

   As soon as the pump is primed, water vapor discharges from the Venturi tube. Then open the discharge gate valve if one is used instead of a check valve; start the pump and close the shutoff valve in the primer. After priming has been completed, the primer handle should be laid over 180° from the priming position to permit the exhaust valve to float in the exhaust stream.

4. By manifold primer (fig. 8-8). The manifold primer can be used on a wide variety of combustion engines which operate on gasoline, natural or LP gas and have four or more cylinders. This primer uses the engine manifold vacuum to evacuate air from the pump casing and suction line. It is equipped with a float valve that provides instant and positive closure as soon as priming is complete to prevent reverse flow during normal pump operation. The manifold primer is almost automatic on most installations; however, it is generally furnished with a reset switch to open the float valve any time it closes prematurely.

   To prime pump, close discharge gate valve, run motor at slow speed, and open shutoff valve of primer. When pump is full of water, close shutoff valve, accelerate engine, and open discharge gate valve.

5. By dry vacuum pump (fig. 8-9). Priming by this method involves the use of a dry vacuum pump powered by an auxiliary motor or belted or geared-to-the-pump motor to evacuate air from the pump casing and suction line. The installation requires a float-controlled air-release valve which will permit air to pass, but will close when water fills the chamber to prevent

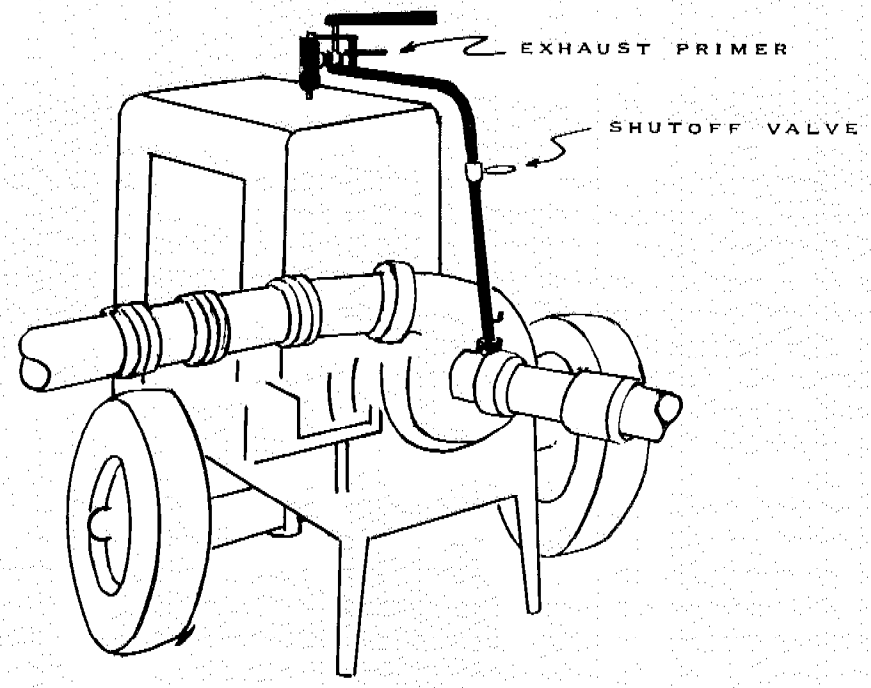


Figure 8-7.--Priming with exhaust primer.

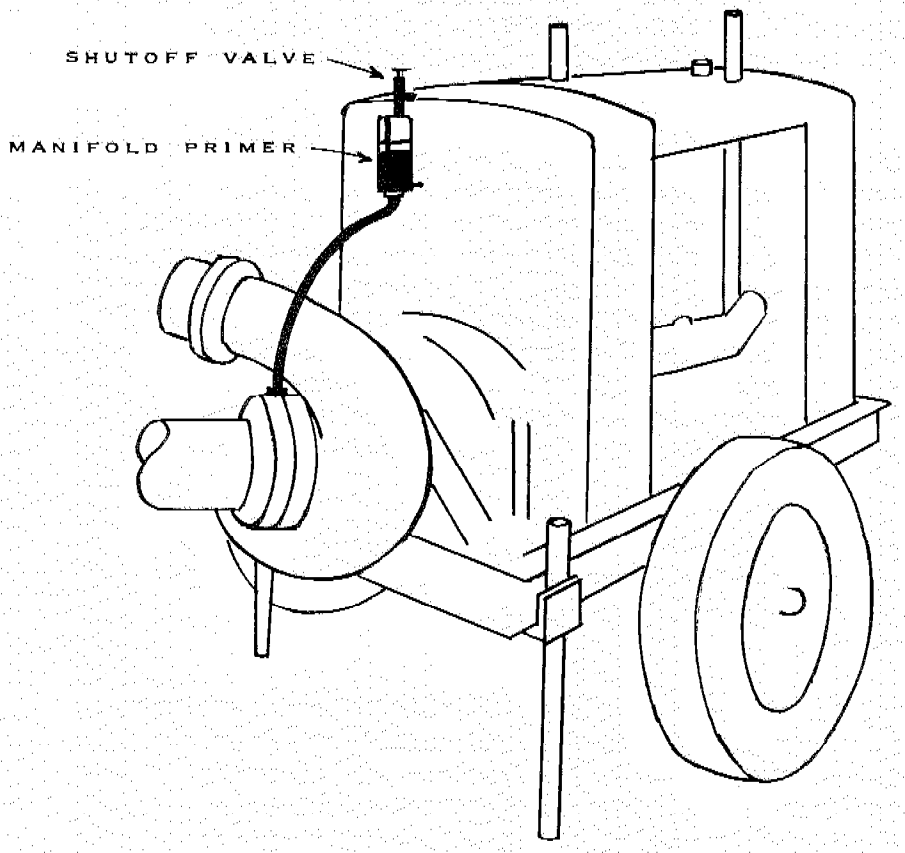


Figure 8-8.--Priming with manifold primer.

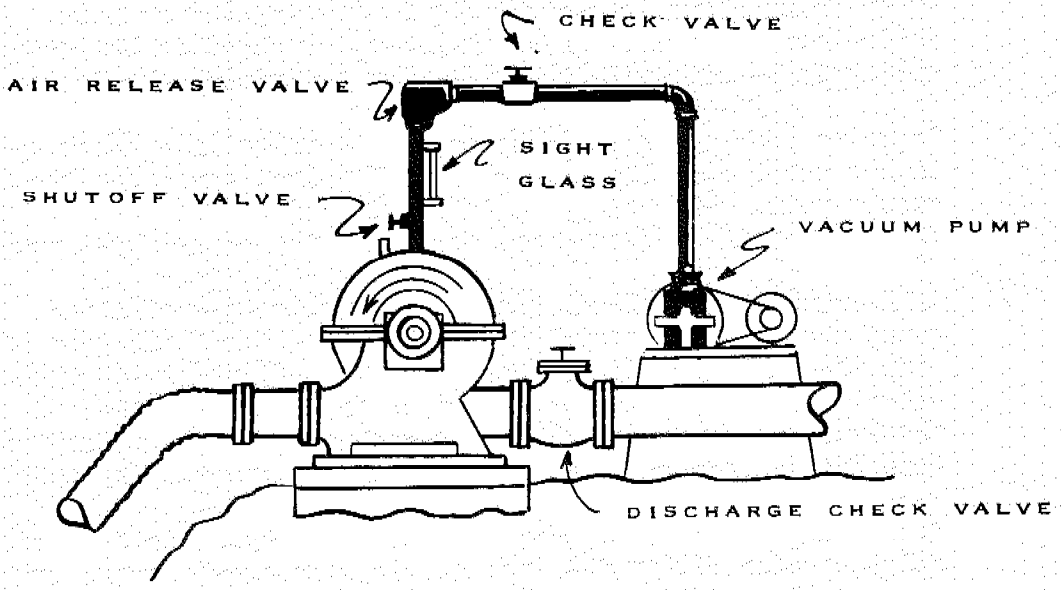


Figure 8-9.--Priming by dry vacuum pump.

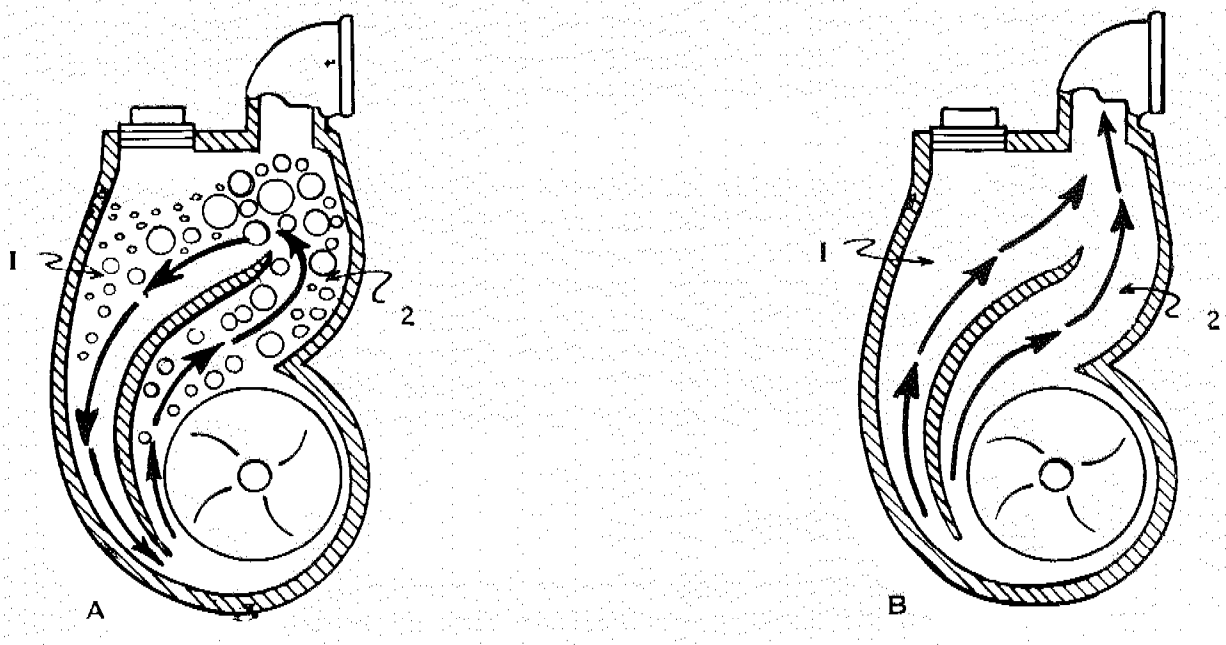


Figure 8-10.--Self-priming centrifugal pumps.

water being drawn into and damaging the dry vacuum pump. A water-level indicator or sight glass, as shown in the drawing, will help to determine when the pump is primed.

To prime pump, open the discharge gate valve if a check valve is not used, open the primer shutoff valve, and start the vacuum pump. When the pump is primed, close the shutoff valve, stop the vacuum pump, and start the centrifugal pump.

6. Self-priming centrifugal pumps. Self-priming centrifugal pumps are made by several manufacturers. With this type of pump the pump chamber and hopper must be first filled with water. Therefore, its advantage is primarily confined to the smaller size pump. They are used extensively by contractors but are generally limited to small irrigation systems.

   After the pump is filled with water, the engine is started, and the water within the impeller is discharged upward into the chamber (fig. 8-10, A). This action instantly creates a vacuum at the impeller eye. Air from the suction line and water within the pump rush into this void. They are mixed at the impeller periphery and discharged upward into the chamber where the air escapes from the water. The force of gravity pulls the heavier air-free water down to the impeller. More air is entrained and the cycle is repeated until the pump is primed.

   When the pump is primed and pumping channels 1 and 2, shown in fig. 8-10, B, become one common discharge channel, the water is no longer circulating within the pump while pumping. The pump is equipped with a check valve at the suction inlet to the pump, and thus the pump is always full of water and priming is automatic after the pump is once filled by hand.

Trouble Checklist.

When the centrifugal pump fails to operate or the discharge or pressure drops, the cause of trouble should be investigated immediately and steps taken to eliminate it. Investigation shows that the majority of troubles with centrifugal pumps, except mechanical failures, can be traced to the suction line, its joints, elbows, foot valves, and other accessories. Air leaks in the suction line must be eliminated to attain the maximum suction lift for a given installation. The following checklist will be helpful in locating the cause of the trouble:

Pump fails to prime.

1. Failure of the pump to prime is mostly occasioned by an air leak in the suction line or in the pump.

2. The most common sources of air leaks are in the threaded connection of the suction line. Coat these connections with pipe cement or white lead and then draw them tight. All connections provided with gaskets must be drawn up tight.

3. The check valve on the discharge side of the pump may have debris lodged between the rubber flap and the valve seat. This will prevent the valve from sealing and forming an air-tight joint.

4. Occasionally, gaskets shrink and admit air into the pump. Tightening the flanges or connections will remedy this difficulty.

5. Rotary shaft seals may leak air if improperly greased or worn. Check this by running the pump and squirting oil on the shaft just outside the seal. If oil is drawn into the seal, a leak is indicated. Filling the seal with grease may eliminate the difficulty, but if the parts are worn, repairs may be necessary. If the seal is always kept full of the proper grade of grease, little, if any trouble will be encountered.

6. Connections in the priming line between the pump and primer must be air-tight or the pump will fail to prime.

7. Screw tight all drain and fill plugs in the pump case to prevent air leaks.

8. A plugged suction line or a collapsed suction hose liner is a frequent source of priming difficulties. Do not overlook this possibility.

<u>Pump fails to develop sufficient pressure or capacity</u>.

1. Check pump speed. The capacity of the pump will vary directly with speed, and pressure will vary with the square of the speed. This means that increasing the speed 20 percent will increase the capacity 20 percent and the head 44 percent. On internal engines, check the governor and adjust if necessary. With electric motors, check to see if motor is across line, wiring correct and receiving full voltage.

2. Check the suction line, strainer, and foot valve. They may be clogged with debris. A frequent source of difficulty is a collapsed suction-hose liner which has the effect of reducing the capacity and pressure the pump develops. The foot valve may be too small or not immersed deep enough to prevent air being drawn in with the water.

3. Check for air leaks in pump or suction line. Air leaks in the suction line or in the pump will occasion a reduction in both capacity and pressure. A small air leak which is not great enough to prevent the pump from priming may reduce both capacity and pressure.

4. Check suction lift. If the suction lift is too high, reduction in capacity will occur. Lifts of more than 20 feet are definitely too high for efficient operation, and the closer the pump can be located to the source of supply, the better will be the results obtained. Refer to Determining Operating Conditions, and discussion on computing suction lift.

5. Check length of suction lines. Long suction lines have the same effect as a high suction lift because of the increased friction when the water passes through the line.

6. Check for worn parts. Worn parts, such as impeller wear rings, will reduce both capacity and pressure. The impeller may be damaged or the casing packing defective.

7. Check impeller for clogging. If the impeller is plugged with foreign material, a reduction in both capacity and pressure will occur.

8. Check piping layout. It is characteristic of centrifugal pumps operated at constant speed that as the pressure is increased, the capacity decreases. In those cases where the pump pressure and capacity are in accordance with the characteristic curve, and when the speed of the engine cannot be increased, if necessary make some alterations in the pipeline so as to reduce the frictional resistance and thereby increase the capacity of the pump.

<u>Pump takes too much power</u>.

1. Check speed of pump. If it is higher than rating, reduce speed to pump rating.

2. Head may be lower than pump rating, thereby pumping too much water.

3. Check for mechanical defects such as bent shaft, binding rotating elements, too tight stuffing box, or misalinement of pump and driving unit.

Pump leaks excessively at stuffing box.

1. The packing may be worn or not properly lubricated.

2. The packing may be incorrectly inserted or not properly run in.

3. Packing is not the right kind or the shaft may be scored.

Pump is noisy.

1. Hydraulic noise-cavitation-suction lift is too high. Check this with a gage.

2. Check for mechanical defects such as bent shaft; binding rotating parts; loose, broken, or worn-out bearings; or misalinement of pump and driving unit.

Deep-Well Turbine Pumps

General.
The deep-well turbine pump used in irrigation is adapted for use in cased wells or where the water surface is below the practical limits of a centrifugal pump. Successful installations have been made where the water surface was 500 feet below the ground. Turbine-pump efficiencies are comparable with those of a good horizontal centrifugal pump. They will give long and dependable service if properly installed and maintained. However, they are usually more expensive than centrifugal pumps and are more difficult to inspect and repair.

Turbine pumps are classified by the type of flow produced by the impeller. The centrifugal type discharges water at right angles to the axis of rotation. In the axial-flow type, the water is given an upward thrust by the impeller similar to a boat propeller. Another type commonly used is a combination of axial-flow and centrifugal and is known as a mixed-flow turbine (fig. 8-11).

Operation.
The turbine has three main parts: the head, the pump bowl, and the discharge column. A shaft from the head to the pump bowl drives the impeller. The bowl is placed beneath the water surface. It has a screen to keep coarse sand and gravel from entering the pump. The turbine pump has stationary guide vanes surrounding the impeller. As the water leaves the rotor, the gradually enlarging vanes guide the water to the casing and the kinetic energy is converted to pressure. The vanes provide a more uniform distribution of the pressure.

In the deep-well turbine pump, the maximum impeller diameter is determined by the diameter of the bowl which is, in turn, restricted by the well diameter. Since well diameters usually are relatively small, the head developed by a single impeller known as a single-stage pump is not great. It is usually necessary to use more than one stage to create the required pumping head with one-stage impeller discharging directly into another. The head produced by such a pump is directly

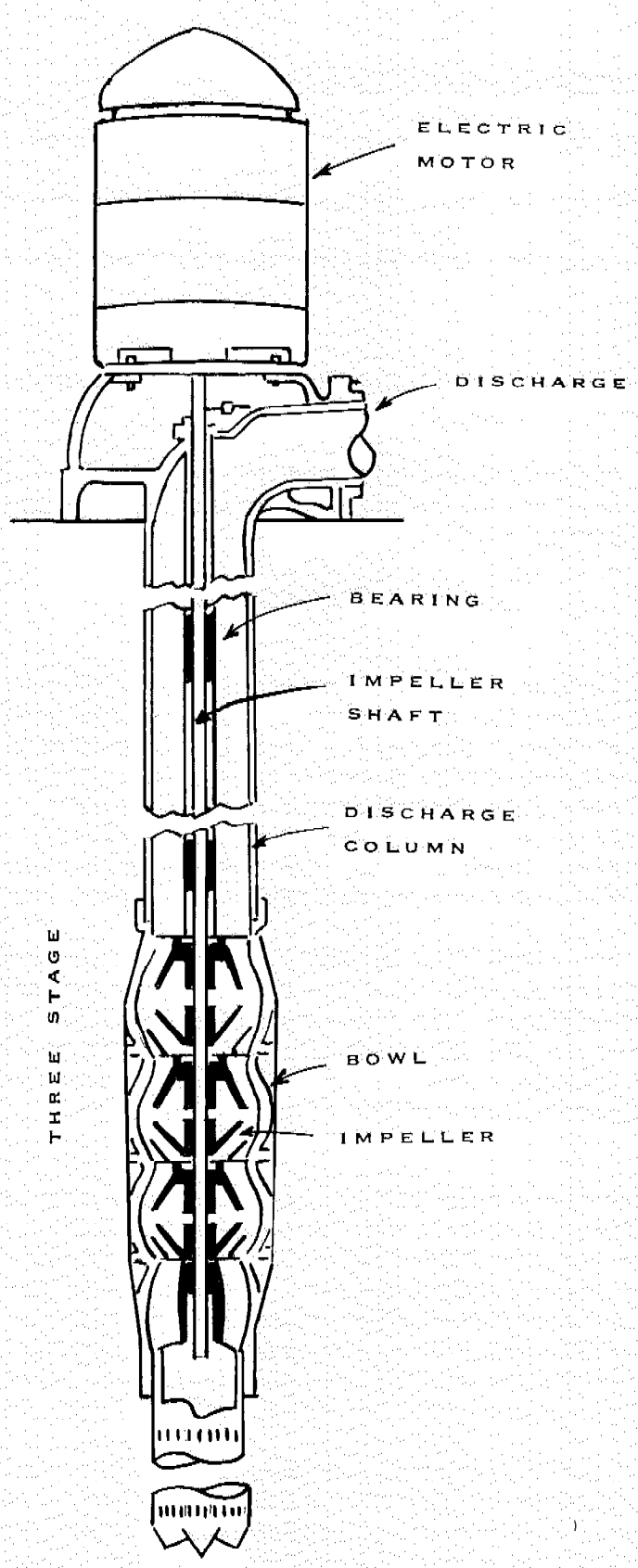


Figure 8-11.--Deep-well turbine pump.

proportional to the number of stages; that is, for given capacity, a two-stage pump will produce twice the head of a single-stage pump, etc.

The type of impeller affects capacity. The capacity is determined by the area through which flow occurs and by the velocity of flows through this area. The velocity is determined by the peripheral speed of the impeller so that the quantity is then determined by the width of the impeller. Of two impellers of the same diameter, the one having greater width will have a greater capacity. The impeller may be designed so that the discharge does not increase so rapidly with reduction in lift and thus an increase in the brake horsepower required at low lift may be avoided. This is an advantage to prevent overloading with changing conditions.

Impellers also may be designed with a higher efficiency over a narrow range of discharges with a rapid decrease in efficiencies under both larger and smaller heads. In wells where fluctuations in lift frequently occur, impellers with flat-topped efficiency curves usually will give higher average efficiencies for all-season operations.

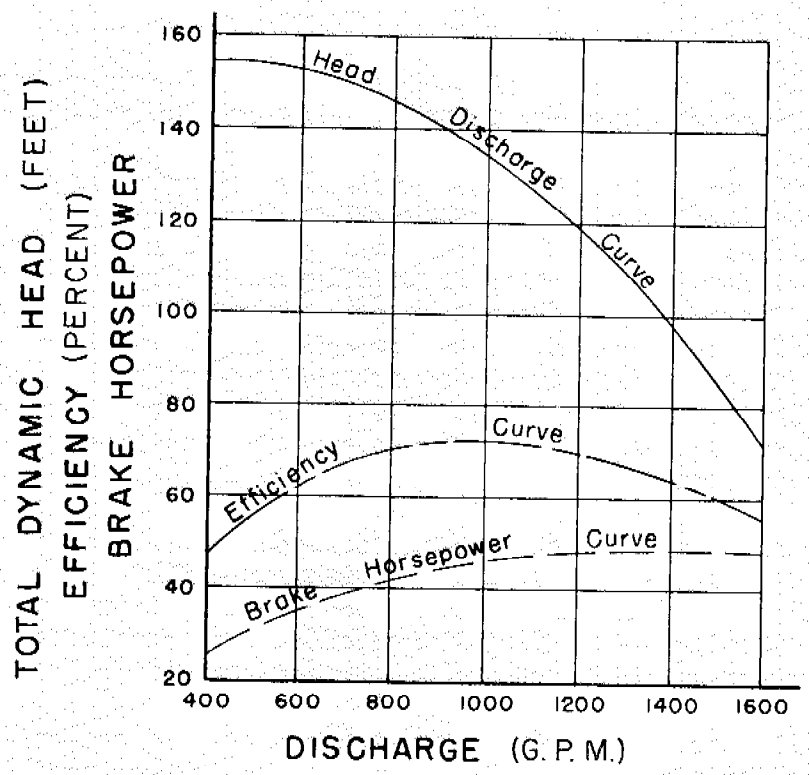
Seasonal fluctuations in the water table should be determined prior to installing the pump so that the bowls of the turbine pump can be placed below the farthest drawdown point. Although a pump is capable of drawing the water below the bowls by drawing on the suction, it is better to have the suction lift in reserve against a lowering of the water table. In locations where fluctuations are apt to occur and it is important to maintain a constant discharge over the anticipated pumping range, a power unit with variable speeds must be used.

In areas of fluctuating water table, it is a good policy to install a water-level measuring device with the pump. This will enable the operator to keep informed of ground-water conditions and to anticipate system alterations and pump replacements.

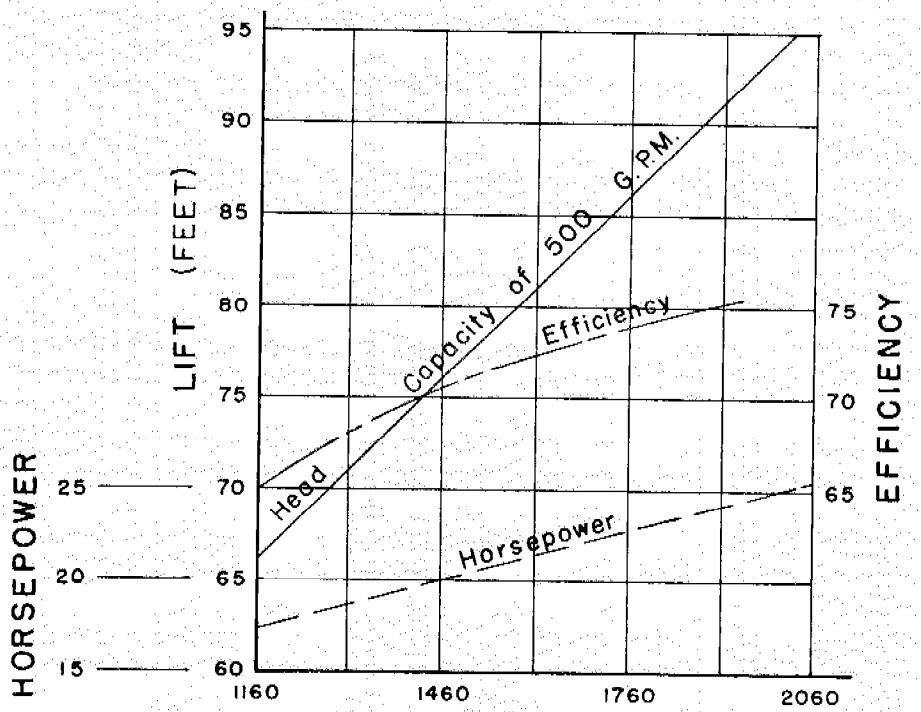
Characteristic Curves.

Characteristic curves of the deep-well turbine pump are determined by test and depend largely on the bowl design and by the speed of the impeller shaft. Head capacity, efficiency, horsepower, and rate of speed are similar to those given for centrifugal pumps. Efficiency curves, in particular, are very similar if the pumps are operated at their designed speed. Turbines, however, cannot operate at a high efficiency over as wide a range of speed as can centrifugal pumps. The reason for this is that a high efficiency is possible only if the vanes in the bowl are in line with the flow of water as it leaves the tip of the impeller. When the speed of the impeller changes, the direction of flow of water leaving the impeller also changes. This causes turbulence against the vane and results in reduced efficiency.

Figure 8-12 shows a typical characteristic curve for a deep-well turbine pump. It is important that the characteristic curves be studied carefully in selecting a pump for any operating condition. If the pump is too large, it will operate too far to the left of its curve; its



A



B

Figure 8-12.--A, Typical characteristic curves for deep-well turbine pump operating at constant speed. B, Heads at which a typical 10-inch turbine pump will deliver 500 g. p. m. together with related factors of pump.

efficiency will be low; and possibly a small increase in head will cause a large decrease in capacity. When the pump is too small, it will operate too far to the right of its curve. Again, this provides poor efficiency. The head developed per stage will be low requiring additional stages that would not have been necessary if a better selection had been made. Figure 8-13 shows the effect of change in operating conditions on pump efficiency.

Pump Selection.

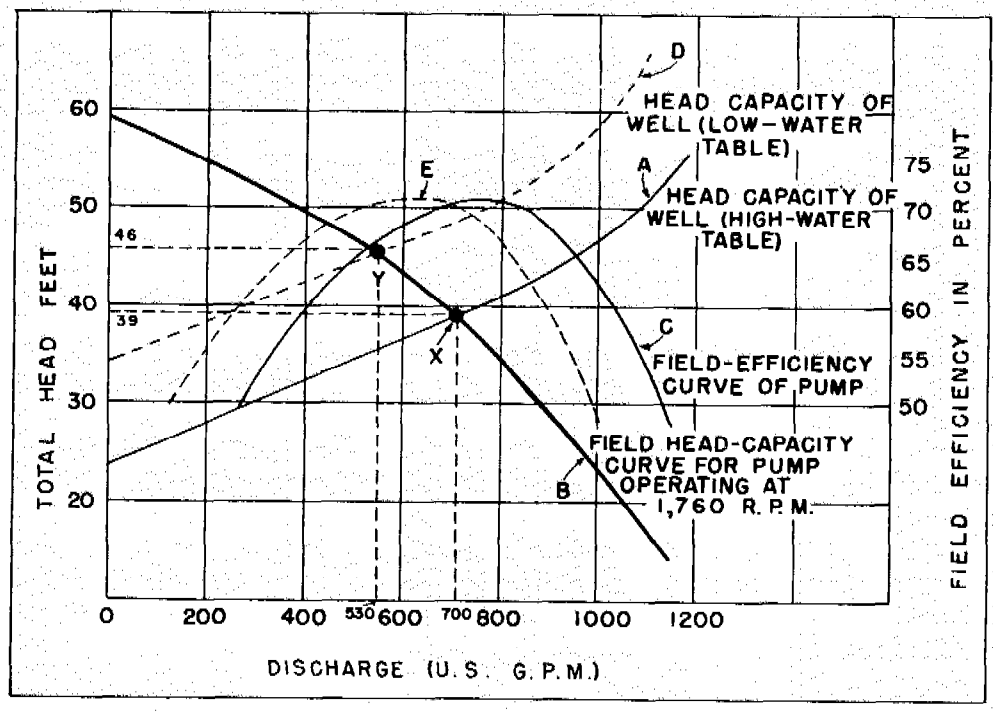
The deep-well turbine pump, as constructed today, is fairly well standardized both as to materials used and general assemblage. Probably the greatest difference between the manufactured units is the design of the bowl and impeller and in the method of lubrication. Some companies offer oil-lubricated pumps; others water-lubricated; and some offer both. Both types have been operating successfully. Wells producing fine sands should be equipped with an oil-lubricated pump. Water for domestic use must be free of oil, and since oil-lubricated pumps waste some oil into the water, it is important that water-lubricated pumps be used.

Each reputable manufacturer has developed a series of pump bowls that have definite characteristics. They have tried to develop a series of bowls that may be used singly or more commonly in a series to meet any combination of head and discharge with a reasonably high efficiency. Possibly the biggest difference between manufacturers is in the efficiency guaranteed over the range of pumping heads and discharges specified. Quite often one manufacturer may be able to meet a range of discharge and lift with a set of bowls at the peak of their performance curve, while another manufacturer may have to utilize a set of bowls that is operating to one side or the other of their best performance to meet the conditions specified.

The selection of the proper sizes of pump column and shaft, type and number of bowls, spacing of bearings and spiders, etc., and the matching of the various units of the pump to meet all well conditions have defied all attempts at simplification and standardization. Most companies offering deep-well turbine pumps have built up their own data from which the various parts of the turbine pump are selected and matched to meet a specific condition. These data are both voluminous and fairly complicated. To specify limiting sizes of pump column and shafting, material used, etc., may result in a pump installation that is more costly, and in some cases less efficient, than could be obtained if the matching of the pump assemblage were left to the bidder. If guaranteed efficiencies and complete description of the unit are specified, it is felt that sufficient data will be obtained to make proper comparisons.

Data for Selecting Pump.

Before any pump selection can be made, it is necessary to have available accurate well data. While a pump can be selected for any head and capacity, an unsatisfactory installation is certain to result unless this pump matches the characteristics of the well. Every well should therefore be tested before a pump is purchased for permanent



At A is shown the head-capacity curve for a well with the high-water-table conditions that often exist in the spring, at the beginning of the pumping season.

The field head capacity for the pump is shown at B. Under these conditions the two curves cross at X, which indicates that this particular pump would deliver 700 gallons per minute with a lift of 39 feet.

A pump is chosen with the highest efficiency, about 71 percent at this point as shown by efficiency curve C. Later in the season the water table may drop 10 feet, and the new head-capacity curve may appear as shown by the dotted line D. This crosses line B at Y which now indicates that only 530 gallons of water will be pumped per minute and that the new head will be 46 feet instead of 39.

The operating point has moved down the efficiency curve, and now the new efficiency is approximately 65 percent instead of 71 percent.

In choosing a pump, it is well to obtain accurate data on the fluctuations of the water table. In this case a pump with an efficiency curve as shown by dotted line E would have served both conditions with high efficiency at all times.

A pump design which produces a flat-topped efficiency curve is advantageous under the conditions shown in the accompanying diagram.

Figure 8-13.--Effect of change in operating conditions on pump efficiency.

installation. These tests should be made with the greatest accuracy, since faulty capacity or head measurements are as bad as no measurement at all. The following information is usually desired by pump manufacturers so that they can determine the type and size of pump needed to fit the characteristics of the well:

Depth of well . . . . . _____ feet
Inside diameter of well casing . . . . . _____ inches
Depth to static water level . . . . . _____ feet
Furnish drawdown-yield relationship curve _____
Seasonal fluctuation in water table . . . _____ feet
Capacity of pump . . . . . _____ gpm
Depth to end of suction pipe . . . . . _____ feet
Is strainer required? . . . . . _____

Type of driver: Electric: voltage_____ phase_____ cycle_____
Gasoline _____ Diesel_____
Natural or LP gas_____ power takeoff_____

Installation.
Most of the installation features discussed under centrifugal pumps also apply to turbine pumps. Deep-well turbine pumps must be in correct alinement between the pump and the power unit, and the pump should be alined in the well casing so that no part of the pump assembly touches the well casing. This is important because vibration in the pump assembly will wear holes in the well casing whenever the two come into contact.

The pump must be mounted on a good foundation so that its alinement between pump and drive and pump and well casing will be maintained at all times. A foundation of concrete provides the most permanent and trouble-free installation. The foundation must be large enough so that the pump and drive assembly can be securely fastened. The foundation should have at least 12 inches of bearing surface on all sides of the well. In the case of a gravel-packed well, this 12-inch clearance should be measured from the outside edge of the gravel packing. When the pump is installed in a gravel-packed well, at least two openings should be provided in the foundation on opposite sides of the well to permit refilling with gravel as the gravel-pack settles (fig. 8-14).

Submersible Pumps

General.
The submersible pump is simply a turbine pump close-coupled to a submersible electric motor attached to the lower side of the turbine. Both pump and motor are suspended in the water, thereby eliminating the long-line shaft and bearing retainers that are normally required for a conventional deep-well turbine pump. Operating characteristics are the same as described for deep-well turbine pumps.

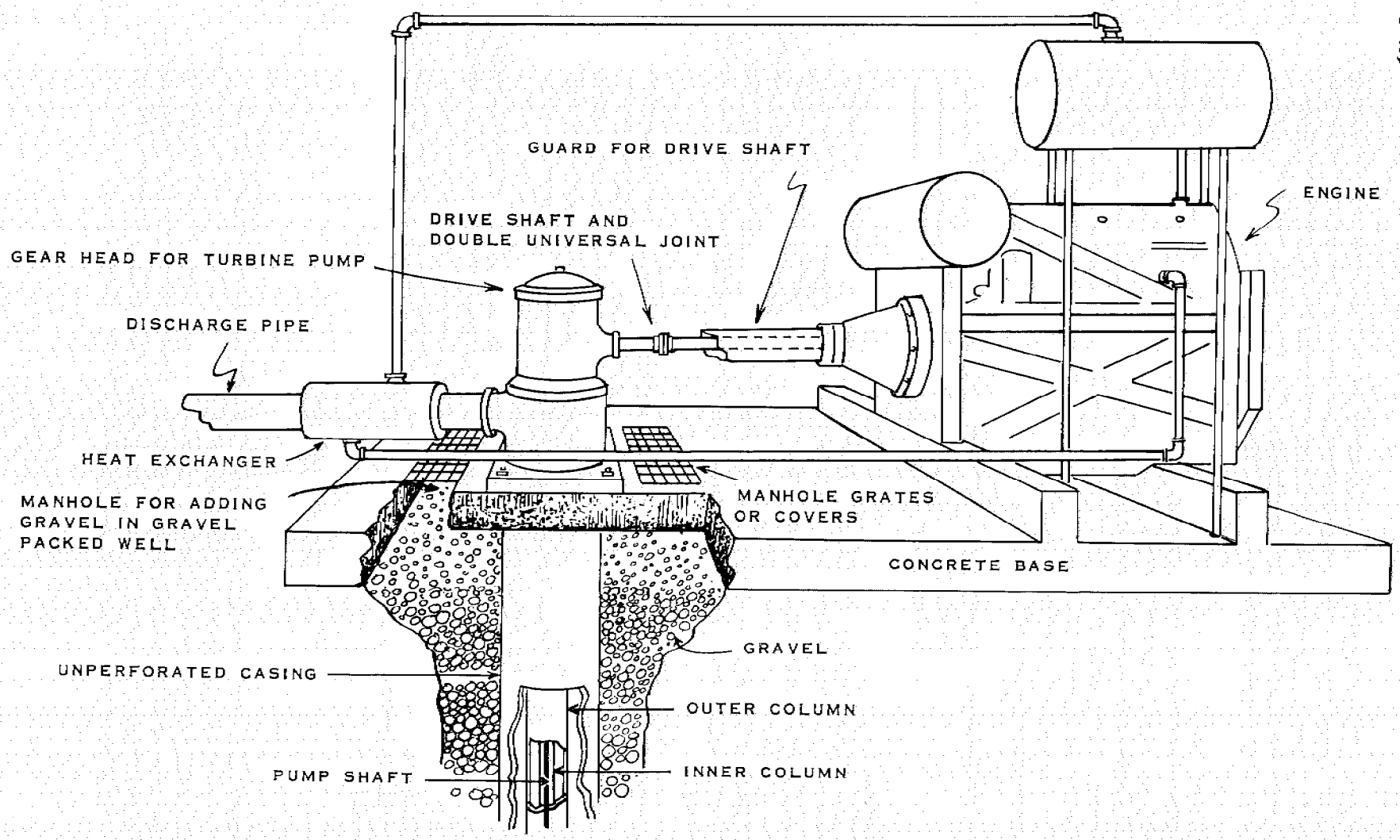


Figure 8-14.--Deep-well turbine pump installation.

Submersible pumps are adapted to cased wells of 4 inches in diameter or larger and settings generally in excess of 50 feet. The short-line shaft makes it particularly adaptable to deep settings and crooked wells. As the submersible pump has no above-ground working parts, it can be used where flooding may be a hazard by sealing the well and placing the starting box, meter, and transformer on a pole above high water. It is also adaptable to locations where above-ground pump facilities would be unsightly or hazardous.

Operation.

The submersible pump consists of a pump and motor assembly, a head assembly, discharge column, and a submarine cable to furnish power to the motor (fig. 8-15).

The pump, being a centrifugal-type turbine, is equipped with either closed impellers or open impellers or some modification of these two types arranged in series. The closed-impeller type is generally used where it is necessary for the pump to develop high pressures. Water enters the pump through a screen located between the motor and pump.

The submersible motors are made smaller in diameter and much longer than ordinary motors so that they may be inserted in wells of the usual diameters. These motors are made in various ways but are generally referred to as dry motors and wet motors. Dry motors are those that are hermetically sealed to exclude the water in the well. These motors run in a high dielectric oil under pressure, which fills the cavity inside the motor, submerging the windings, bearings, and rotor. Various provisions are made to prevent the entrance of water into the motor. External cooling of the oil is accomplished by the flow of water around the motor.

Wet motors are those in which the well water has access to the inside of the motor with the rotor and bearings actually operating in the water. In this type of motor, the windings of the starter are usually completely sealed off from the rotor by means of a thin, stainless steel inner liner. A filter around the shaft is required to prevent the entrance of abrasive material into the motor. This type of motor must be filled with water during installation so that the bearings will have sufficient lubrication when the motor is first started.

Installation.

The discharge pipe connects the pump to the head assembly. This pipe must be long enough to provide complete submergence of both the pump and the motor at all times. Initial cost of installing the submersible pump is low. Ease in installation is an outstanding feature as it is necessary only to add the required length of discharge pipe to lower the unit to the proper setting. The head assembly should rest on and be securely fastened to a concrete base that covers the well casing. Since the complete pump and motor assembly is in the well, no pump house is required, thus providing a saving in the installation cost. The control panel, however, which includes an entrance switch, meter, magnetic starter, and, in the case of a dry motor installation, an oil well safety control, should be enclosed in a waterproof box.

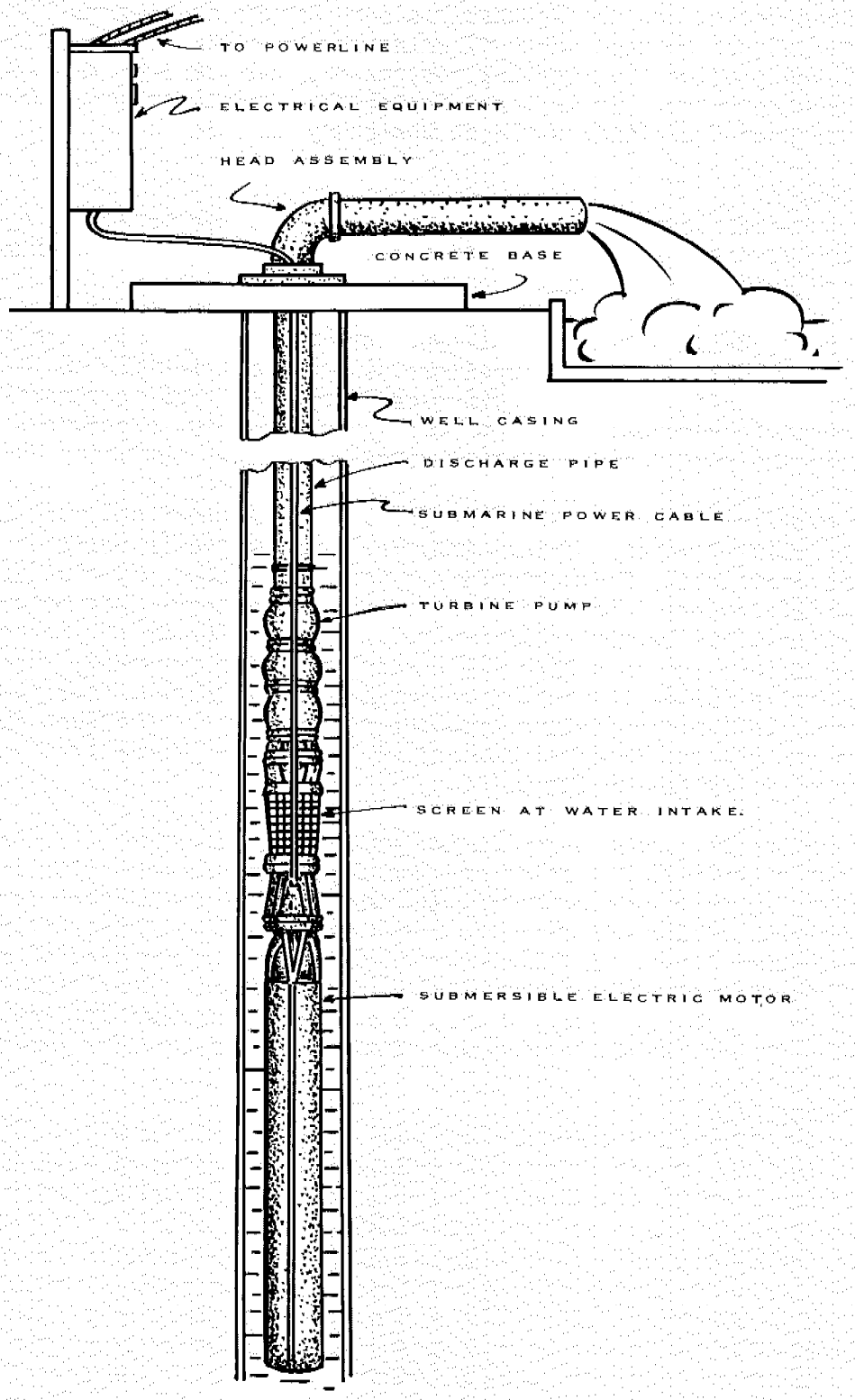


Figure 8-15.--Submersible pump.

Propeller Pumps

General.
There are two types of propeller pumps, the axial-flow or screw type, and the mixed flow. The major difference between the axial-flow and the mixed-flow propeller pump is in the type of impeller (fig. 8-16).

The principal parts of a propeller pump are similar to the deep-well turbine pump in that they have a head, an impeller, and a discharge column. A shaft extends from the head down the center of the column to drive the impeller. Some manufacturers design their pumps for multi-stage operation by adding additional impellers where requirements demand higher heads than obtainable with single-stage pumps.

Where propeller pumps are adapted, they have the advantage of low first cost and the capacity to deliver more water than the centrifugal pump for a given size impeller. Also, for a given change in pumping lift, the propeller pump will provide a more nearly constant flow than a centrifugal pump. Their disadvantage is that they are limited to pumping against low heads.

Axial Flow.
The axial-flow single-stage propeller pumps are limited to pumping against heads of around 10 feet. By adding additional stages, heads of 30 to 40 feet are obtainable. These pumps are available in sizes ranging from 8 up to 48 inches. The impeller has several blades like a boat propeller. The blades are set on the shaft at angles determined according to the head and speed. Some manufacturers have several propellers for the same size of pump, thereby providing for different capacities and heads. The water is moved up by the lift of the propeller blades and the direction of flow does not change as in a centrifugal pump. A spiral motion of the water results from the screw action but may be corrected by diffusion vanes.

Mixed Flow.
The mixed-flow propeller pump is designed especially for large capacities with moderate heads. The smaller size single-stage pump will operate efficiently at low heads of from 6 to 26 feet. The multiple stage and large size pumps will handle heads up to approximately 125 feet. They are generally built in sizes ranging from 10 to 30 inches. The mixed-flow pump uses an open vane curved blade impeller which combines the screw and centrifugal principles in building up the pressure head. They have a capacity range of from 1,000 g. p. m. to approximately 50,000 g. p. m. depending on size, stages, and heads. The mixed-flow pump operates more efficiently against higher heads than the axial-flow propeller pump.

Operating Characteristics.
Power requirements of the propeller pump increase directly as the head so adequate power must be provided to drive the pump at maximum lift. There is some tendency for a propeller pump to overload as head is increased. For this reason, it is important to select a motor which will provide ample power to drive the pump through the entire range of conditions due to change in water level or discharge pressures. Propeller

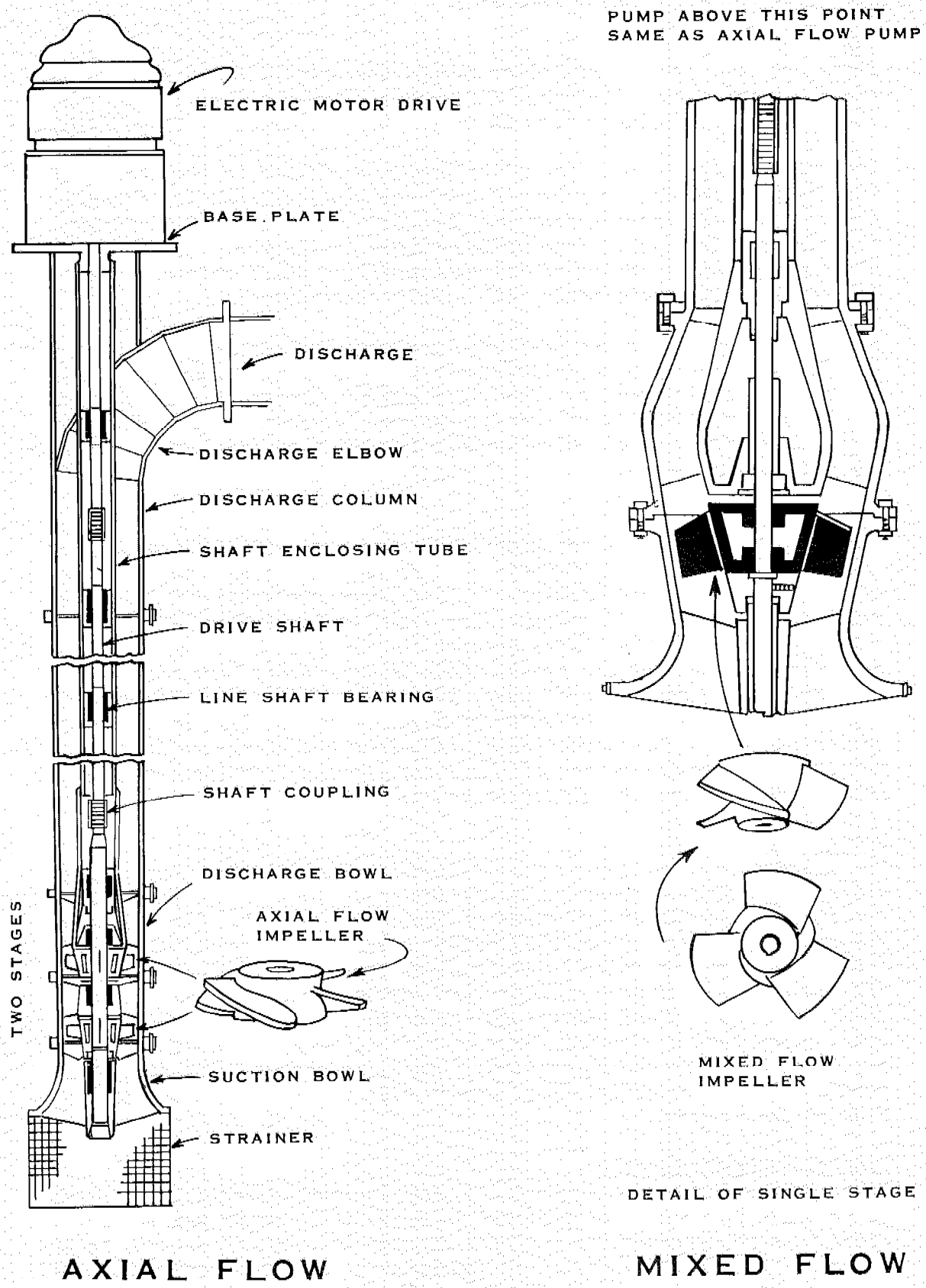


Figure 8-16.--Propeller pumps.

pumps are not suitable under conditions where it is necessary to throttle the discharge to secure reduced delivery. It is important to accurately determine the maximum total head against which this type of pump will operate.

Propeller pumps are not suitable for suction lift. The impeller bowl must be submerged with the pump operating at the proper submergence depth. Different makes and sizes of pumps require different submergence depths. Therefore, the recommendations of the pump manufacturer should always be followed. Failure to observe required submergence depth may cause severe mechanical vibrations and rapid deterioration of propeller blades.

It is also important that proper clearances be maintained between the end of the suction pipe and the side walls and bottom of the pit or pump-intake bay. Failure to observe manufacturers' recommendations on this point can result in lowering of efficiencies. When two or more pumps are installed in one pump bay, they must be separated far enough so as not to interfere with each other. The pump manufacturers have specifications for this distance. In general, this distance should be three times the diameter of the bell at the suction end of the pump measured between bells.

Some manufacturers recommend that each pump have its own sump. This can be obtained by constructing a baffle wall between adjoining pumps reaching from the sump floor to the water level in the sump. When each pump has its own sump, the distance between pumps is controlled by the required clearance between end of bell and side wall of the sump. See figure 8-17 for measurement of clearances and an example of some required clearances specified by one manufacturer.

Characteristic Curves.

Characteristic curves for propeller pumps are quite similar to those for turbine pumps and show head capacity, efficiency, and horsepower for a given pump size, type of impeller, and discharge (figure 8-18).

Propeller pumps are made by most of the nationally known pump manufacturers and by many small local machine shops. The large pump companies have rating curves developed by actual tests. These rating curves take into account all losses in the pump.

The locally manufactured pump generally lacks the hydraulic-design requirements incorporated in the nationally known pumps. The result is that they are generally cheaper to buy but have higher operating costs, particularly for higher heads. Very few of the small local companies have made sufficient tests to develop adequate rating curves. Generally, for static lifts up to about 4 or 5 feet, losses in the pump are not so important and these locally manufactured pumps may be fairly efficient.

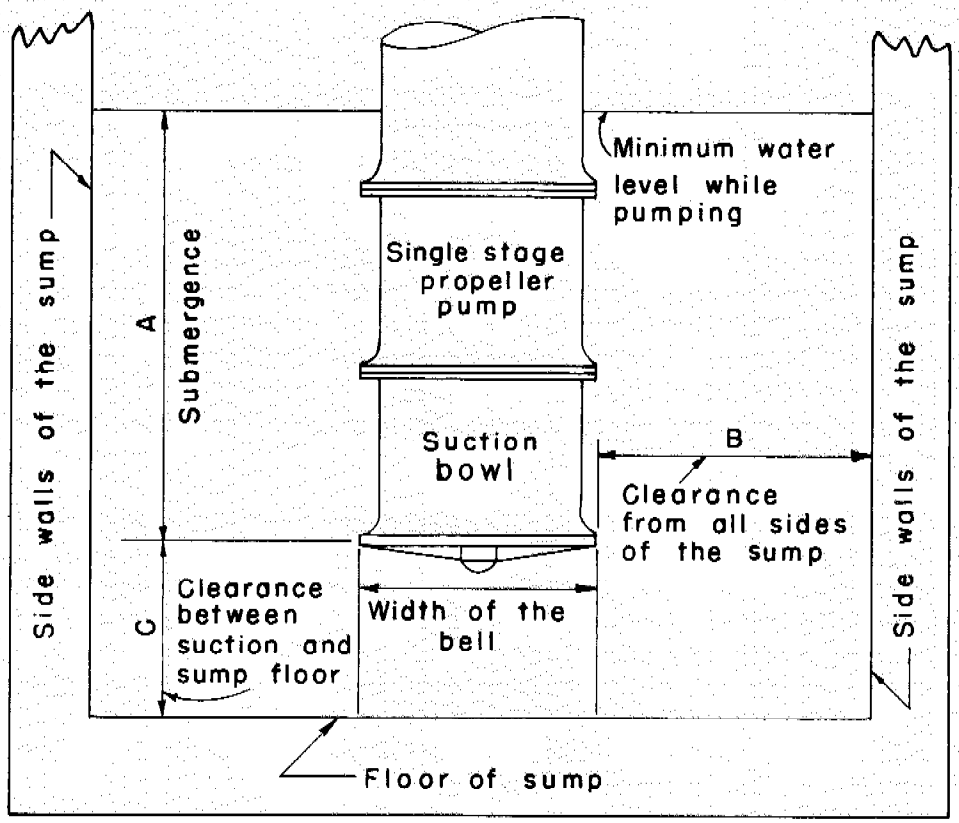


Table showing manufacturer's recommendations of clearances for propeller pump:			
Pump size	A Amount of submergence	B Clearance between pump and side walls	C Clearance between suction end and sump floor (without strainer)
8	2'-2"	12"	7"
10	2'-6"	15"	8"
12	2'-9"	18"	10"
14	3'-0"	21"	12"
Where two pumps are used, the clearance between bells should be 41", 50" and 66" respectively for 8, 10, 12 and 14 inch pumps.			

Figure 8-17.--Clearance required for propeller pump.

Curves shown are obtained by testing pumps with 10 foot column including enclosed discharge elbow with head measurements taken in a horizontal discharge pipe at least three pipe diameters beyond elbow flange.

Discharge column losses should be added when settings are deeper than 10 feet.

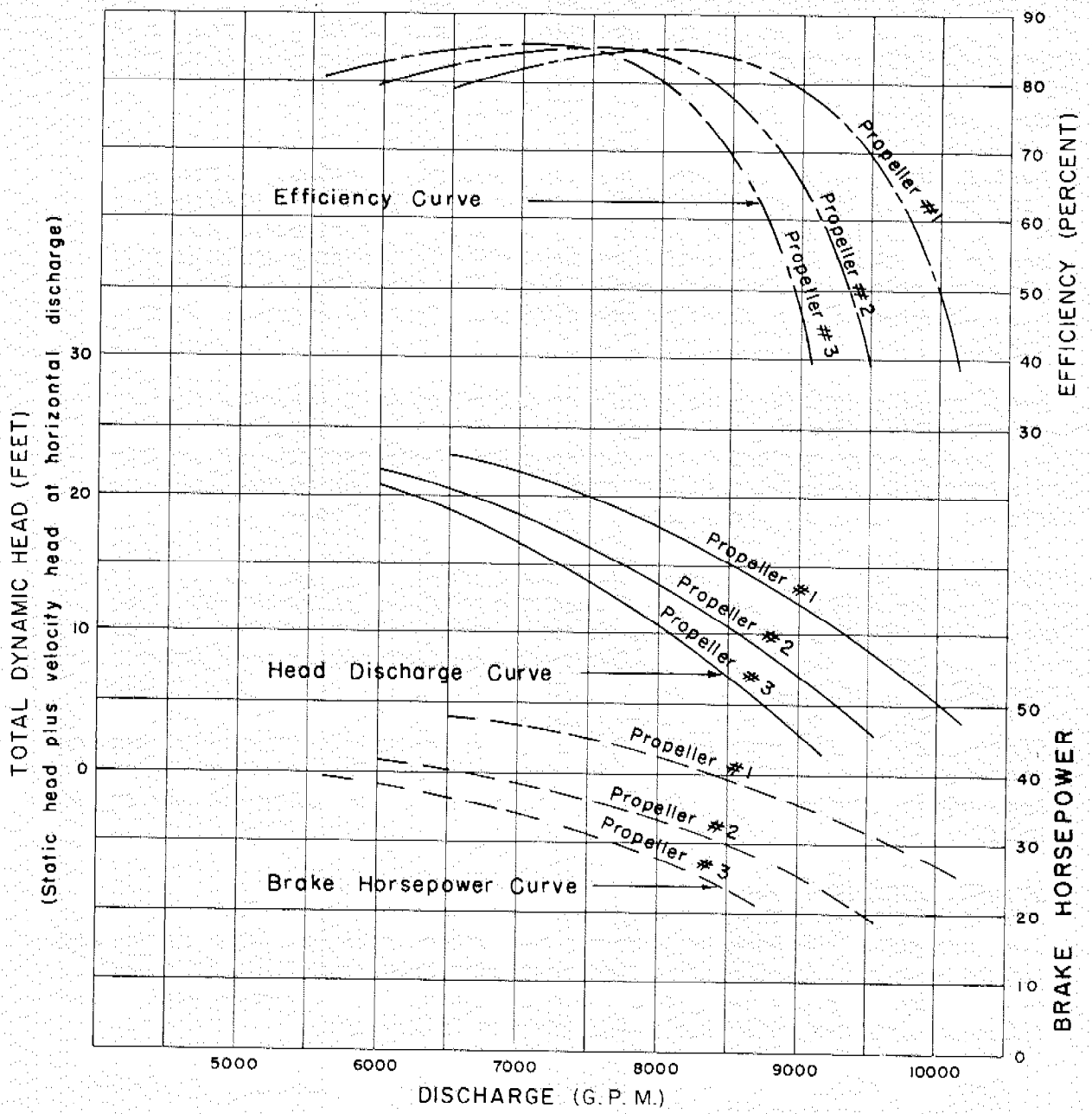


Figure 8-18.--Typical characteristic curves for an 18-inch axial-flow single-stage propeller pump with three different type propellers.

Installation.
The vertical propeller pump should be set on a firm, adequate foundation and securely fastened so that it will withstand the pump vibrations as well as the dead load of the pump and structure. The entire weight of the complete pump unit is supported by the base or floor plates. The foundation should be designed to support this weight evenly on all sides of the base plate and allow the unit to hang perpendicular through the floor opening provided for it. It is important to obtain uniform support for the base plate so as to avoid deflection of the pump column.

Generally the pump is fastened to a floor supported either on piling or on the sides of the intake bay or sump. If a partially enclosed pump bay is used, it should preferably be square. A circular shape tends to accentuate the rotation of the water in the sump which may seriously interfere with pump operations. The installation of baffle plates attached to the sides of the sump will help to overcome this trouble.

The 45° angle propeller pump should be installed with the same care as outlined for the vertical pump. Since this pump must set at an angle to the pump bay and water surface, it is necessary to so arrange the supporting beams so that the pump's base plate can be securely fastened in line with the manufacturer's recommendations.

Some type of strainer or screen should be installed to exclude floating wood or other debris that would damage the impeller if drawn into the pump. Some manufacturers provide a small strainer that can be attached to the suction bowl. These strainers work satisfactorily when water is pumped that is comparatively free of floating vegetation and small debris. When the source of water supply contains this type of foreign material, the small strainer is apt to become clogged. When this happens, it is wise to construct some type of screen around the inlet of the intake bay or sump so as to increase the area for straining out the small debris.

Data for Selecting Pump.
In general, the data needed for properly selecting a propeller pump and driver are about the same as that for the other types of pump. Reasonably accurate data must be furnished the pump manufacturer for him to select from his line of propeller pumps the one that will be the most efficient for the job. These data should include the following:

Capacity of pump . . . . . _____ g. p. m.
Discharge conditions: (show by sketch)
(a) discharge above water level
(b) discharge submerged
(c) siphon.

Static lift . . . . . _____ feet
Strainer: Yes_____ No_____
Length of discharge pipe . . . . . _____ feet
Number of bends or curves . . . . . _____
Types of power: electric - voltage ____phase _____
cycle_____ combustion engine _____
Type of driver: direct-connected vertical hollow shaft motor _____
vertical - pulley _____V-belt_____

Determining Operating Conditions

General.
A pump operates most satisfactorily under a head and at a speed approximately that for which it was designed. The operating conditions should therefore be determined as accurately as possible. A common mistake is overstating the head conditions. The correct practice is to give the head as closely as possible to the actual figure. If there is a variation in head, both maximum and minimum heads should be determined and furnished to the manufacturer for the selection of the most satisfactory pump.

Determining Head for Centrifugal Pumps.
In determining head for centrifugal pumps, it is necessary to calculate the total dynamic head (t. d. h.) considering both the suction and discharge sides of the pump. Therefore, the total dynamic head is equal to the total dynamic suction lift plus the total dynamic discharge head less suction velocity head.

Computing total dynamic suction lift. Suction lift is composed of the following factors (see fig. 8-19):

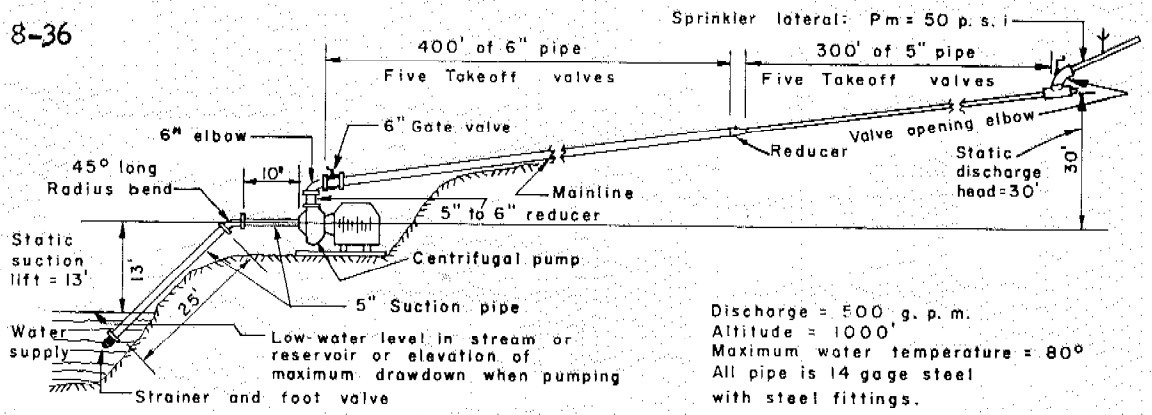
1. Static suction head (actual vertical distance of center of pump above lowest water surface after pumping begins).

2. Friction head in pipelines.

3. Head losses in elbows, strainers, foot valves, and other accessories.

4. Velocity head.

Atmospheric pressure determines the maximum practical suction lift. Atmospheric pressure not only varies with altitude and temperature, but also varies with weather conditions. As the pressure on the water at sea level is one atmosphere or 34 feet, the highest theoretical suction lift at sea level is 34 feet less friction losses. This maximum theoretical suction lift cannot be obtained under actual conditions. Pump manufacturers usually recommend that the design suction lift be limited to 70 percent of its theoretical value.



Problem: Check total dynamic suction lift and total dynamic head.

Compute total dynamic suction lift —

	Feet
1. Static suction lift	13.00
2. Friction head in pipelines: Suction pipe = (25' + 10') = 35' 35' of 5" pipe at 500 g.p.m. = 35' X 0.0593 Ft/Ft.	2.08
3. Friction head in fittings:	
5 inch 45° long radius bend ($h_f = K \times \frac{V^2}{2g}$ = 0.18 X 0.99)	.18
Foot valve ($h_f = K \times \frac{V^2}{2g}$ = 0.8 X 0.99)	.79
Strainer ($h_f = K \times \frac{V^2}{2g}$ = 0.95 X 0.99)	.94
Velocity head ($\frac{V^2}{2g}$)	.99
Total Suction Lift	17.98

Note: Reference to table 8-1, page 8-37, shows the maximum design static siphon lift at altitude of 1000 feet with water temperature of 80° F. is 22'. System as designed is within limit of practical suction lift.

Compute total dynamic discharge head

	Feet
1. Static discharge head	30.00
2. Friction head in pipelines: 400' of 6" pipe at 500 g.p.m. = 400 X .0236	9.44
300' of 5" pipe at 500 g.p.m. = 300 X .0593	17.79
3. Friction head in fittings:	
One 5 to 6" increaser ($h_f = [1 - 25/36]^2 \times \frac{V^2}{2g}$ = 0.09 x 0.99)	.89
One 6" standard 90° elbow ($h_f = K \times \frac{V^2}{2g}$ = 0.28 X 0.48)	.13
One 6" Gate valve, open ($h_f = K \times \frac{V^2}{2g}$ = 0.11 X 0.48)	.05
Five 6" takeoff valves (same as gate valve open=0.11 X .48 X 5)	.25
Four 5" takeoff valves (same as gate valve open=0.13 X .99 X 4)	.51
One take off valve and valve opening elbow, operating ($h_f = K \times \frac{V^2}{2g}$ = 12 X .99)	11.78
One 6 to 5" reducer ($h_f = 0.7[1 - 25/36]^2 \times \frac{V^2}{2g}$ = 0.7 x 0.93 X 0.99)	.64
4. Velocity head at end of discharge pipe (5" pipe at 500 g.p.m.)	.99
5. Pressure required to operate lateral (50 p.s.i. X 2.31')	115.50
Total discharge head	187.97

T.D.H. = Total dynamic suction lift + total dynamic discharge head — suction velocity head

T.D.H. = 17.98 + 187.97 − 0.99 = 204.96'

Figure 8-19.—Example of determining head for centrifugal pumps.

The computed dynamic suction lift must not be more than the maximum design static siphon lift. If a suction lift is greater than the maximum design static siphon lift, the system will not operate properly under designed conditions. In other words, the discharge will drop below the required amount to a point where friction and velocity head are sufficiently decreased. When this condition exists, the static lift should be decreased or a larger suction pipe used to decrease the friction loss.

Table 8-1 gives the maximum design static siphon lift based on altitude and water temperature:

Table 8-1.— Maximum design static siphon lift in feet

Altitude (ft.)	Temperature				
	60°F.	70°F.	80°F.	90°F.	100°F.
0	23.4	23.2	23.	22.6	22.2
500	23.	22.8	22.5	22.2	21.8
1,000	22.4	22.3	22.	21.8	21.4
1,500	22.	21.9	21.6	21.4	20.9
2,000	21.6	21.5	21.2	20.9	20.5
3,000	20.8	20.6	20.4	20.1	19.7
4,000	20	19.9	19.6	19.3	18.9
5,000	19.2	19.1	18.8	18.6	18.1
6,000	18.5	18.3	18.1	17.8	17.4
7,000	17.8	17.6	17.4	17.1	16.7
8,000	17.1	16.9	16.7	16.4	16

Computing total dynamic discharge head.--All losses on the discharge side of the pump must be accurately computed. The total dynamic discharge head is composed of the following factors (see fig. 8-19):

1. Static discharge head which is the actual vertical distance measured from the centerline of the pump to the centerline of the pipe at the discharge end, or to the surface of the water at the discharge pool, whichever is greater.

2. Friction head in the pipeline. (For sprinkler systems, the laterals are not included -- only the main and supply line.)

3. Friction head developed in the elbows, reducers, valves, and other accessories.

4. Velocity head at end of discharge pipe.

5. Pressure required at end of line. For sprinkler systems, this is the pressure required to operate the lateral. When the system is designed to discharge freely into a ditch or reservoir, no additional pressure is required.

Determining Head for Deep-Well Turbine Pumps.
The total dynamic head for deep-well turbine pumps differs somewhat from centrifugal pumps in that suction lift is not involved because the impellers of the pump are submerged. Losses in the pump and pump column are included in the pump efficiency and should not be included when figuring the total dynamic head. Therefore, the total dynamic head is composed of the following factors (fig. 8-20):

1. Static head which is the actual vertical distance in feet measured from the water level in the well when pumping the required discharge to the centerline of the pipe at the discharge end.

2. Friction head in the discharge pipeline.

3. Head losses in elbows, reducers, valves, and other accessories.

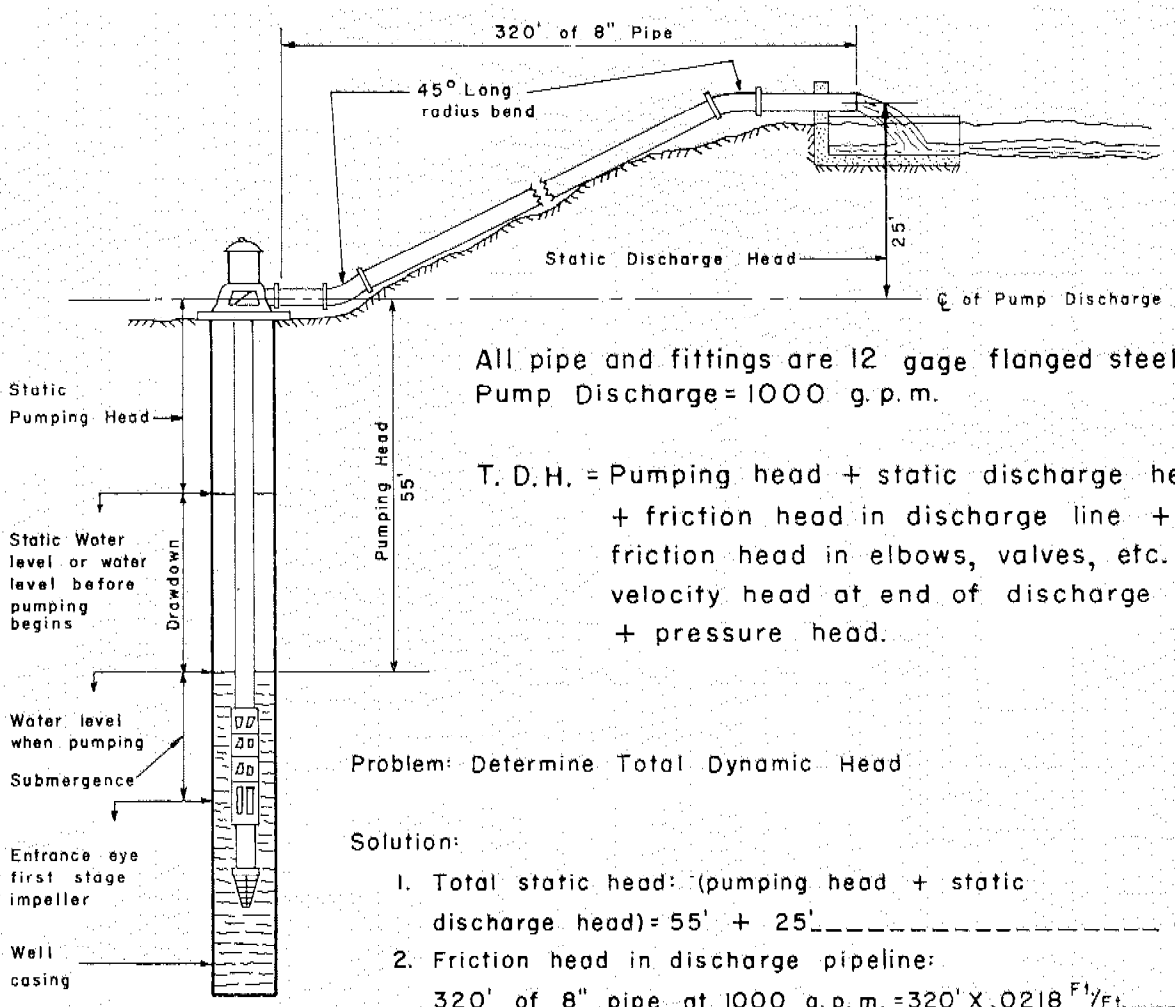
4. Velocity head at the end of the discharge pipe.

5. Pressure required at the end of the discharge pipe.

Determining Head for Propeller Pumps.
The total dynamic head for propeller pumps is similar to that for deep-well turbine pumps and is composed of the following factors (fig. 8-21):

1. Static head which is the actual vertical distance measured from the low-water level in the pump bay to, as shown in figure 8-21, (a) centerline of pipe at the discharge end when the water level is below the pipe at the discharge end; (b) to the water surface at the discharge end when the pipe is submerged; (c) to water level in discharge bay when installation is made to take advantage of siphoning.

   In the case of a siphon installation at the start of pumping, it is necessary to raise the water to the highest point in the line to fill the discharge pipe. The siphoning action will then start and as soon as this occurs, some reduction in head will take effect. No additional power will be required; however, capacity will be reduced until siphoning starts. The limit to practical siphon lift depends upon altitude above sea level, water-vapor pressure at water temperature, velocity head at high point in the siphon, and head loss in the siphon piping.



All pipe and fittings are 12 gage flanged steel
Pump Discharge = 1000 g. p. m.

T. D. H. = Pumping head + static discharge head + friction head in discharge line + friction head in elbows, valves, etc. + velocity head at end of discharge pipe + pressure head.

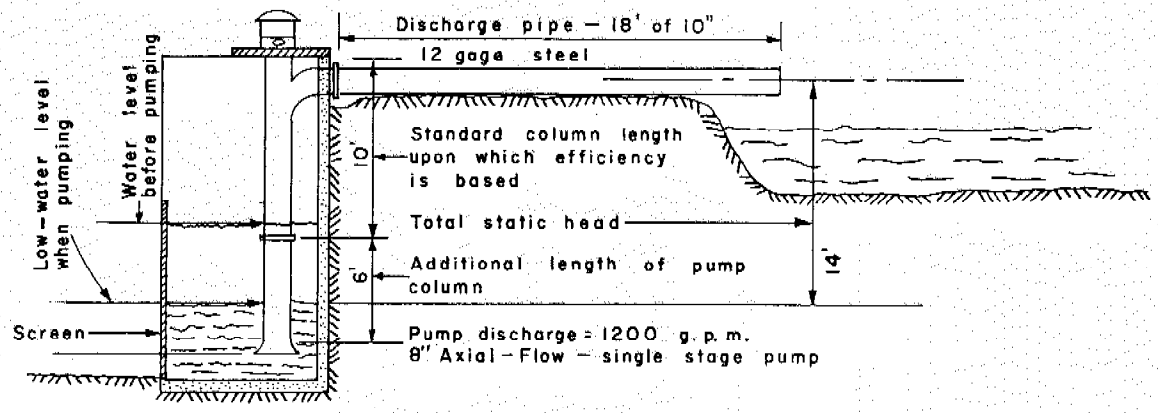
Problem: Determine Total Dynamic Head

Solution:

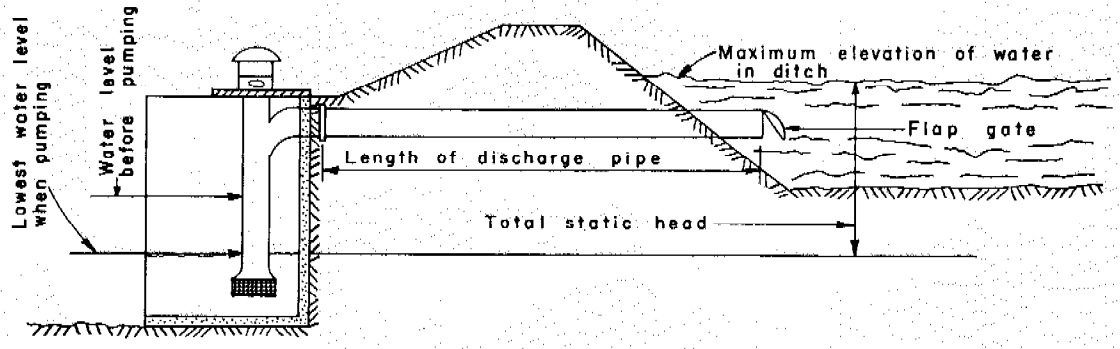
	Feet
1. Total static head: (pumping head + static discharge head) = 55' + 25'	80.00
2. Friction head in discharge pipeline: 320' of 8" pipe at 1000 g. p. m. = 320' X .0218 Ft/Ft.	6.98
3. Friction head in fittings: Two 45° long radius bends ($h_f = K \times \frac{V^2}{2g} = 0.17 \times 0.64$) X 2	.22
4. Velocity head at end of discharge pipe: $\frac{V^2}{2g} = \frac{6.41}{64.4} = 0.64$	.64
5. Pressure head	.00
Total dynamic head	87.84

Figure 8-20.--Example of determining head for turbine pumps.

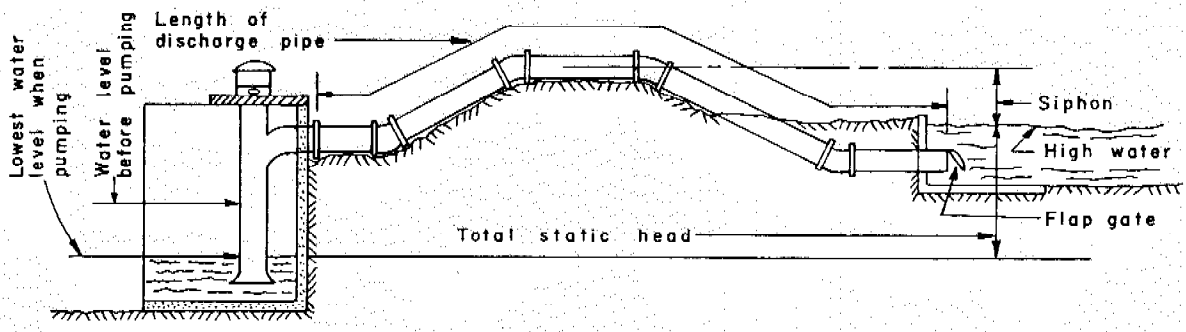
(a.) WATER LEVEL BELOW PIPE AT DISCHARGE END



(b.) WATER LEVEL ABOVE PIPE AT DISCHARGE END



(c.) DISCHARGE END OF PIPE SUBMERGED FOR SIPHON ACTION



Problem: Determine total dynamic head for (a.) above for a capacity of 1200 g. p. m.

Solution:—

	Feet
1. Total static head (pumping level to ℄ discharge pipe)	14.00
2. Friction head in additional 6' of pump column: 8" pipe at 1200 g.p.m. = 6' X .0307	.18
3. Friction head in discharge line: 10" at 1200 g.p.m. = 18' X .01	.18
4. Friction head in fittings: (no strainer-screen on pump bay)	.00
5. Velocity head at end of discharge for 10" pipe $(\frac{V^2}{2g})$ =	.34
Total T. D. H.	14.70

Figure 8-21.--Example of determining head for propeller pumps.

2. Head losses in pump column pipe, pump discharge elbow and suction bowl -- these losses are generally included when the pump efficiency is determined.

   Some companies base their efficiency on a standard length of pump column. If a longer length than the standard is used, the friction loss for this additional length must be added in determining the total dynamic head.

3. Friction head in the discharge pipeline.

4. Head losses through flap valves and strainer.

5. Velocity head at the end of the discharge pipe.

The velocity head and friction losses can be reduced by enlarging the discharge pipe. Generally, a smooth iron discharge pipe should be 2 to 4 inches larger than the pump elbow. Corrugated pipe will require a correspondingly higher increase in size. The increase in size should not be made abruptly. An expanding section 3 to 4 feet long should be used to connect the pump to the discharge pipe.

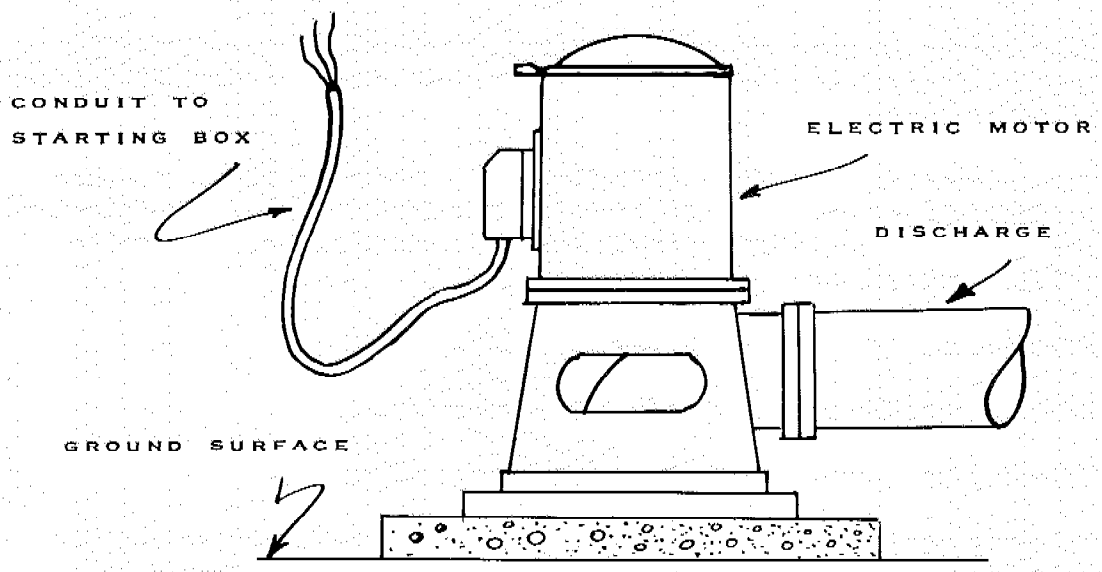
Drives

General.
The efficiency of a drive mechanism may greatly affect the operating costs of a pumping installation. Four common types of drives are usually used in irrigation pumping: direct, belt, 90° gear head, and power takeoff.

Direct Drive.
The direct drive is the most efficient as there is no loss of power as with other drives. It is limited to those conditions where the speed of the driver is the same as that for the pump. For horizontal centrifugal pumps, the drive may be through a flexible coupling (fig. 8-1), or it may be close coupled (fig. 8-22).

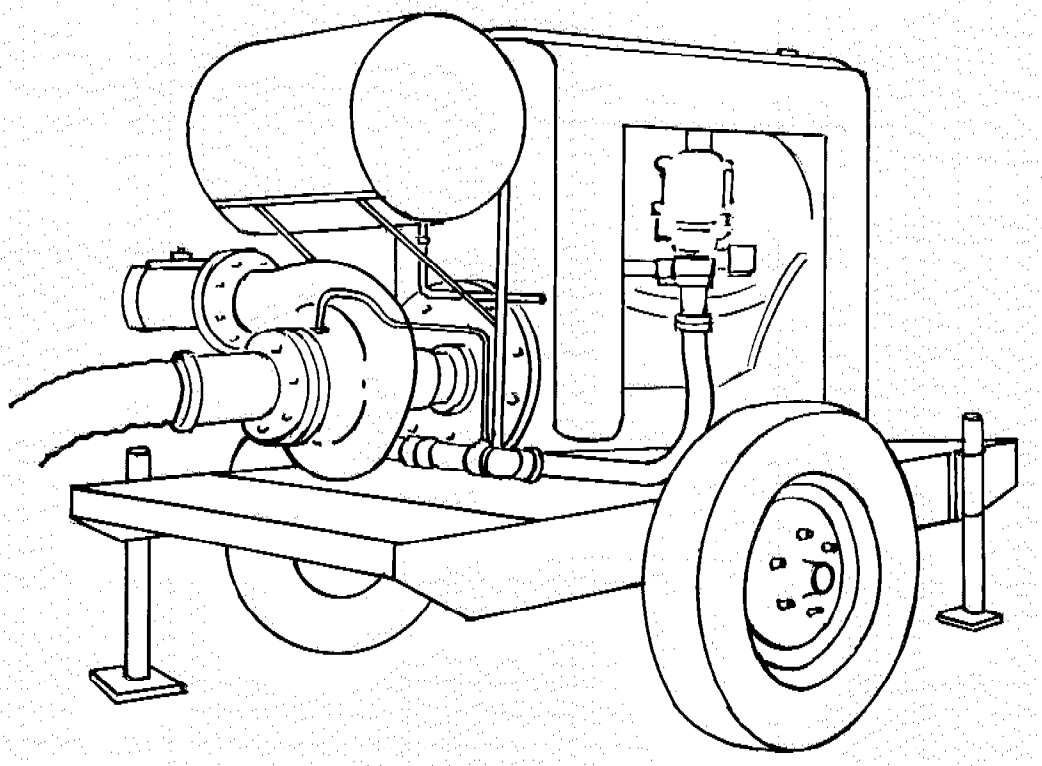
When a flexible coupling is used, the motor may be removed for another use or for servicing without disconnecting the pump-piping arrangement. With a close-coupled pump assembly, the pump and its prime mover are always in mechanical alinement with the result that possible power losses and mechanical difficulties occasioned by misalinements are avoided.

For deep-well turbine pumps using an electric motor, the direct drive (fig. 8-22) is the cheapest and most efficient type of drive. However, since electric motors operate at a constant speed, the discharge of the pump cannot be varied; thus, extreme care must be exercised in selecting the size of the pump. Direct drives may also be used with vertically mounted internal combustion engines.



DIRECT CONNECTED TURBINE PUMP

ELECTRIC MOTOR



DIRECT CONNECTED CENTRIFUGAL PUMP

GASOLINE MOTOR

Figure 8-22.--Examples of direct drive.

Belt Drive.
Belt drives are either flat-belt or V-belt.

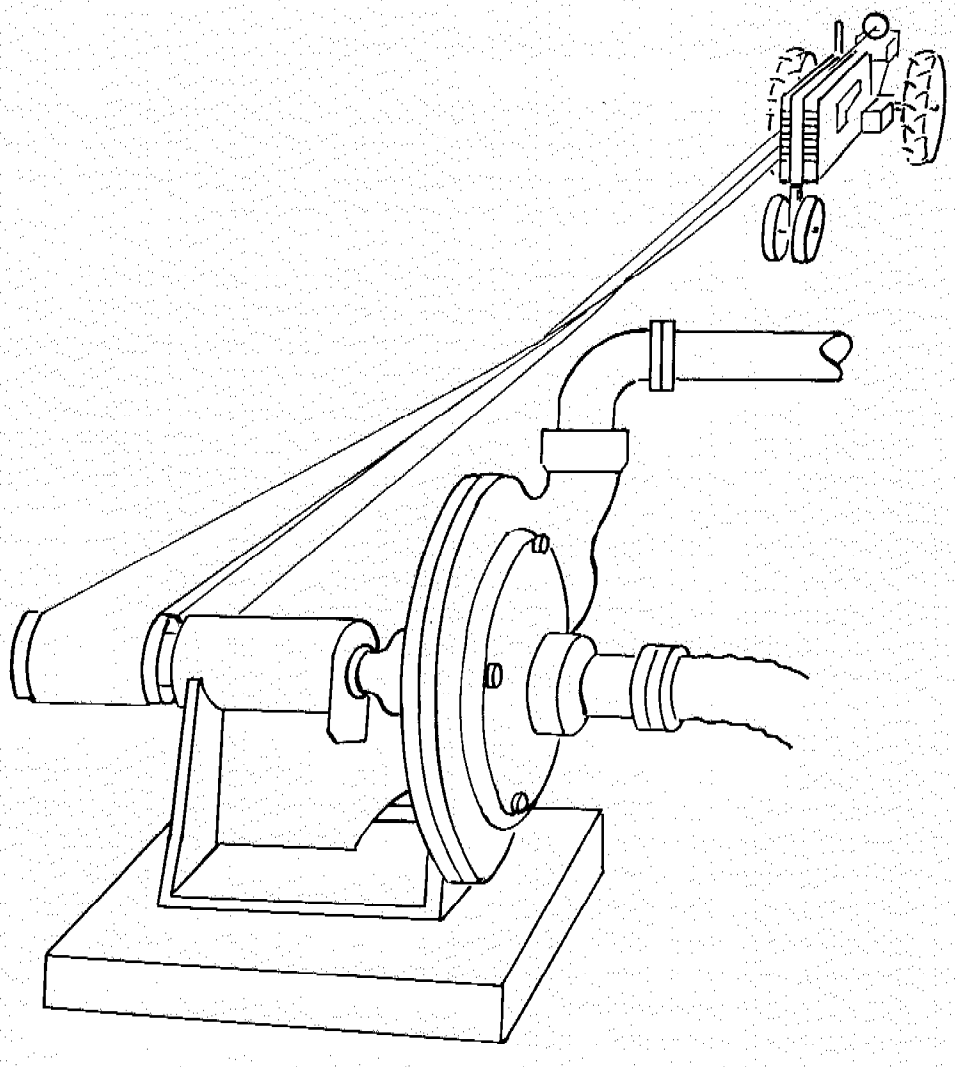
The flat-belt is the least efficient of all the types of drives (fig. 8-23). Its efficiency varies considerably, usually from 80 to 90 percent, depending upon slippage, type of pulley and belt, pulley size, number of idlers, and the twist used.

Slippage usually accounts for the most loss of efficiency. Slippage may be caused by the belt being too loose, too stiff, or too narrow. Slippage is also caused by small pulleys, pulley centers too close together pulling from the top instead of the bottom, or by placing the belt at too steep a vertical angle. Quarter turns, half turns, and idler pulleys will add to the inefficiency of flat-belt drives. The relation of pulley size to belt thickness and horsepower capacity is important. When heavy belts are turned about a small-diameter pulley, the outer fibers are greatly overstressed and the belt life is materially shortened. Power ratings are based on tensions when large pulleys are used and are reduced for small pulleys to compensate for increasing flexing. Refer to figure 8-24 for determining size and speed of pulleys.

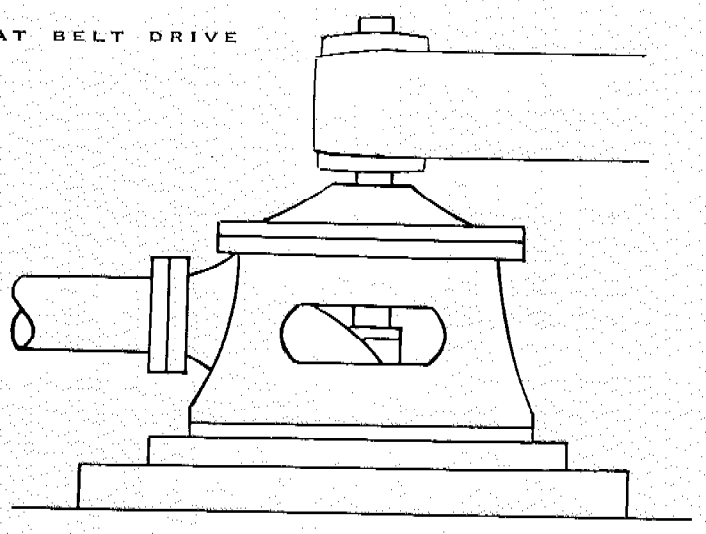
A belt-driven installation requires considerable attention because the variation of temperature and humidity between morning and midday or day and night affects the tension on the belt and running position on the pulley. A low belt may cause edge rubbing on the mounting and damage the belt. A tight belt will cause it to slip off the pulley. The flat-belt is generally employed to make use of a source of power that is already available on the farm. Farm tractors are quite often used as a source of power using a flat-belt drive. Stationary and internal combustion motors, either gas or Diesel, and horizontal electric motors are also used.

The V-belt drive is more dependable and has a higher efficiency than flat-belt drives. When properly installed, it should have an efficiency of from 90 to 95 percent. The V-belt drive will operate successfully when pulley centers are much closer together than are permissible with flat-belts. Therefore, they can be utilized successfully in confined spaces. Special grooved pulleys are required for V-belt drives. It is important to use the proper belt and pulley size. For this reason it is best to have the V-belt manufacturer make the design for each particular installation. A large number of belts on a quarter-turn drive is undesirable because the distance between pulley center changes, and it is not possible for all belts to have the same tension. This condition is one of the reasons why very short pulley centers are not permissible on quarter-turn drives. V-belt installations cost slightly more than flat-belts; however, they are less expensive than a right-angle gear drive (figs. 8-24 and 8-25).

90° Gear Heads.
The right-angle gear drive is the most dependable and efficient method of transmitting the power of a combustion engine to a turbine

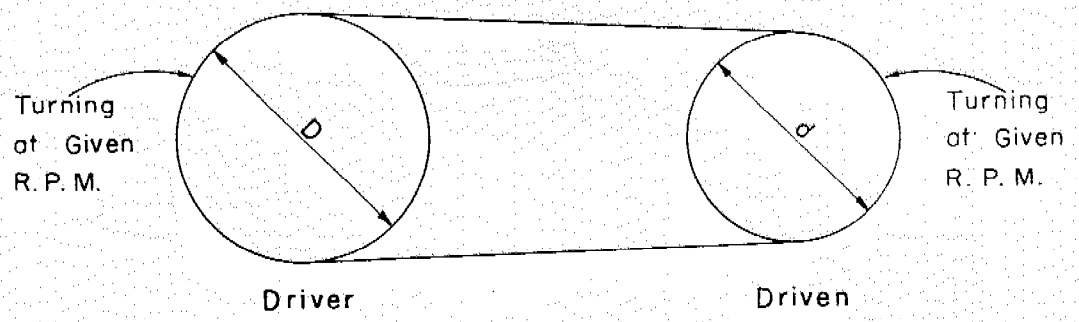


CENTRIFUGAL PUMP WITH FLAT BELT DRIVE



TURBINE PUMP WITH FLAT BELT HEAD

Figure 8-23.--Examples of flat-belt drive.

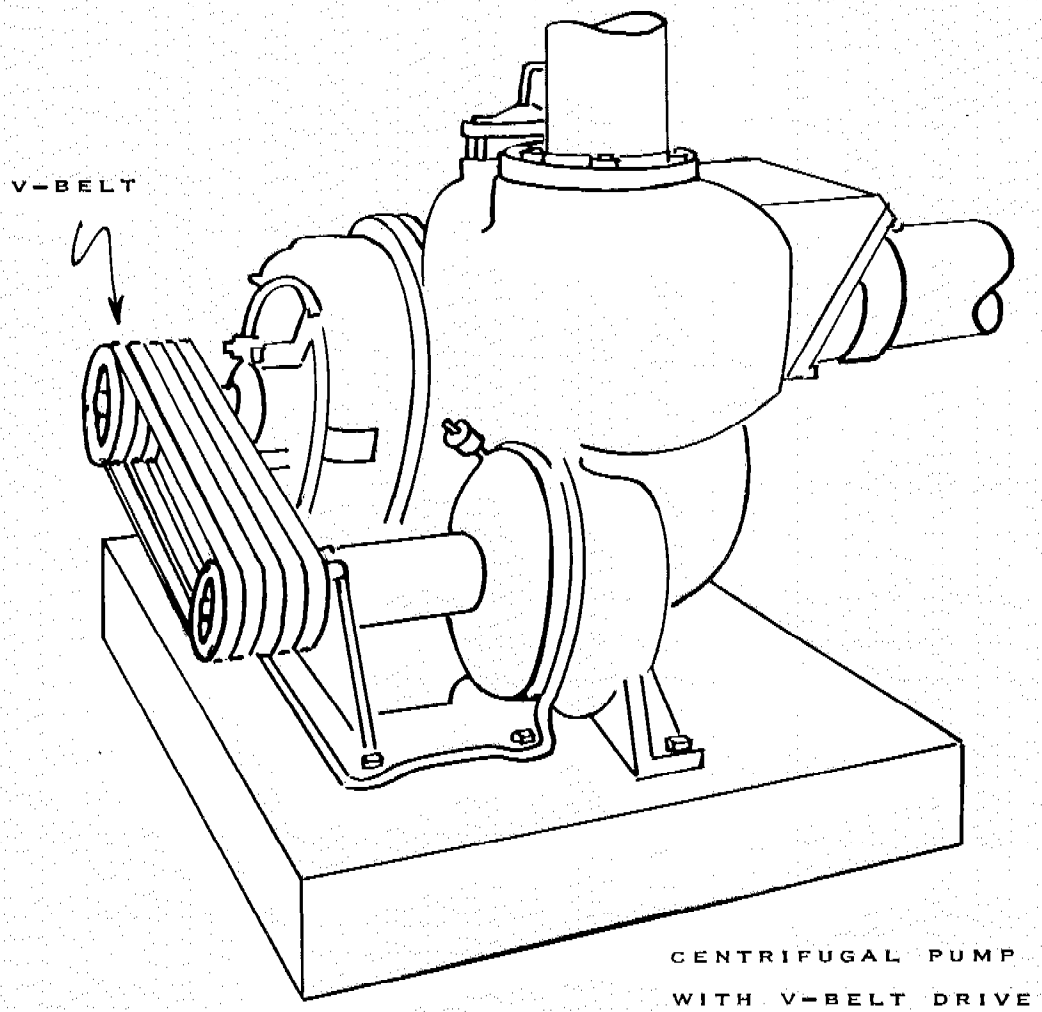


The driving pulley is called the driver and the driven pulley the driven.

If the number of teeth in gears or sprocket wheels is used instead of diameter in these calculations, number of teeth must be substituted whenever diameters occur.

1. To determine diameter of driver, the diameter of the driver and its revolutions, and also revolutions of driver being given.
   Diameter of driver (D) = $\frac{\text{diameter of driven (d) X revolutions of driven (R.P.M.)}}{\text{Revolutions of driver (R.P.M.)}}$
2. To determine diameter of driven, the revolutions of the driven and diameter and revolutions of driver being given.
   Diameter of driven (d) = $\frac{\text{diameter of driver (D) X revolutions of driver (R.P.M.)}}{\text{Revolutions of driven (R.P.M.)}}$
3. To determine the revolutions of driver, the diameter and revolutions of driven, and diameter of driver being given.
   Revolutions of driver (R.P.M.) = $\frac{\text{diameter of driven (d) X revolutions of driven (R.P.M.)}}{\text{Diameter of driver (D)}}$
4. To determine the revolutions of the driven, the diameter and revolutions of driver and diameter of driven being given.
   Revolutions of driven (R.P.M.) = $\frac{\text{diameter of driver (D) X revolutions of driver (R.P.M.)}}{\text{Diameter of driven (d)}}$

Figure 8-24.--Rules for determining size and speed of pulleys, sheaves, gears, or sprocket wheels.



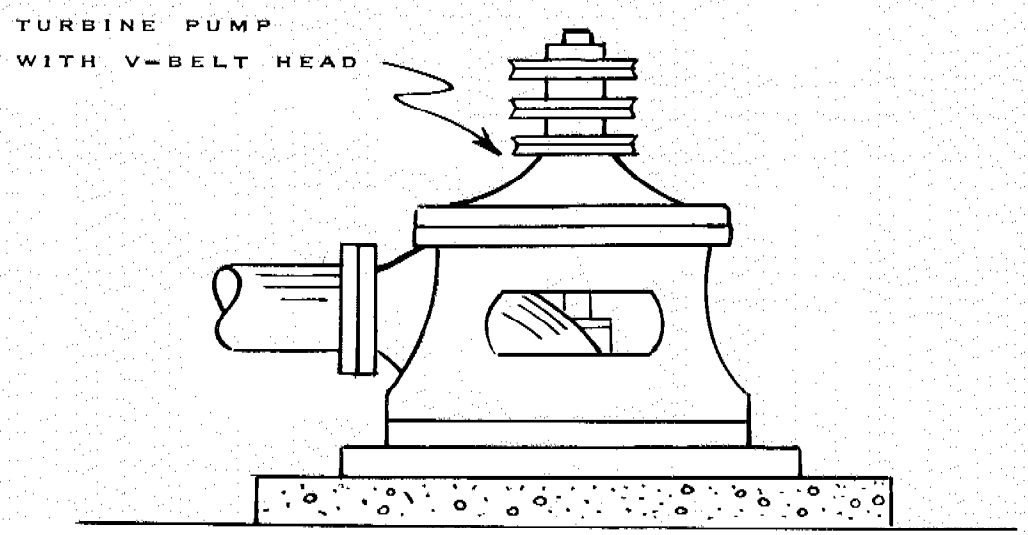


Figure 8-25.--Examples of V-belt drives.

pump. The efficiency of this type of installation is 95 percent or more. These units are made to fit any standard pump and are made with a variety of gear ratios to permit the pump and engine to operate at their most efficient speeds. The original cost of right-angle gear drives slightly exceeds the cost of the V-belt or flat-belt installation. For steady pumping and dependability, the right-angle gear drive is preferred. It not only is more efficient but also is not affected by weather and temperature conditions.

The head containing the gears replaces the ordinary pulley head, and the drive shaft may be directly connected to an engine or motor. The drive shaft should always contain a flexible or universal joint. The universal joint will take care of any errors or changes in alinement of pump and engine. The distance between the pump and engine should not be less than 3 feet because small errors or changes in alinement will not materially affect the smoothness and efficiency of power transmission (fig. 8-26).

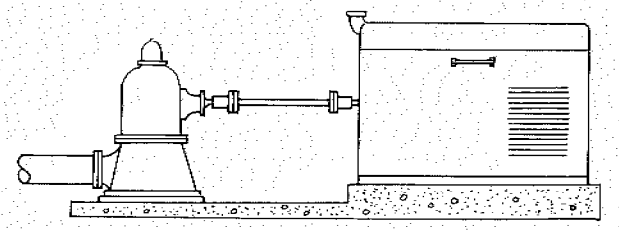
Power Takeoff.
The use of a farm-type tractor with power takeoff is rapidly increasing as a means of power, particularly for small centrifugal pumps. The standard power-takeoff speed is 540 plus or minus 10 r. p. m. Irrigation pumps commonly operate at three to four times this speed, making it necessary to use some type of speed increaser between the tractor power-takeoff shaft and the pump-impeller shaft. The pump and speed increaser are commonly mounted either on a two-wheel trailer unit hitched to the tractor drawbar or directly on the tractor. The desired increase in speed is usually obtained through the use of spur gears, beveled gears, or V-belts. With spur gear speed increasers, the propeller shaft of the pump should be approximately parallel to the power-takeoff shaft with spur gears providing the desired increase in r. p. m. In the beveled gear type, the pump-impeller shaft is approximately at right angle to the power-takeoff shaft with beveled gears providing the change of direction and increase of r. p. m. The third type employs V-belts and sheaves alone, or in combination with gears to obtain the required pump speeds (fig. 8-27).

Reasonable care should be exercised to be sure that the power-takeoff shaft is properly alined. The universal joint-yokes on the telescoping portion of the power-takeoff shaft should be in the same plane. This is necessary to eliminate as nearly as possible the variable speeds of rotation and the resulting vibration, shock, and universal joint wear (fig. 8-28).

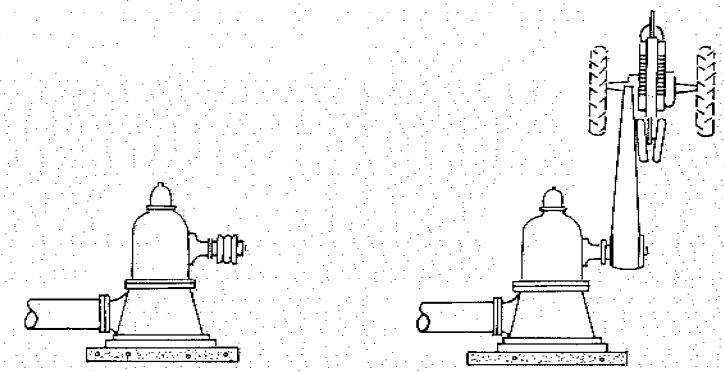
Cavitation

Cavitation is a term used to describe a rather complex phenomenon that may exist in a pumping installation. In a centrifugal pump this may be explained as follows:1/When a liquid flows through the suction line and enters the eye of the pump impeller, an increase in velocity takes place. This increase in velocity is, of course, accompanied by a reduction in pressure. If the pressure falls

1/ Courtesy of Fairbanks, Morse & Company, and Economy Pumps, Inc.

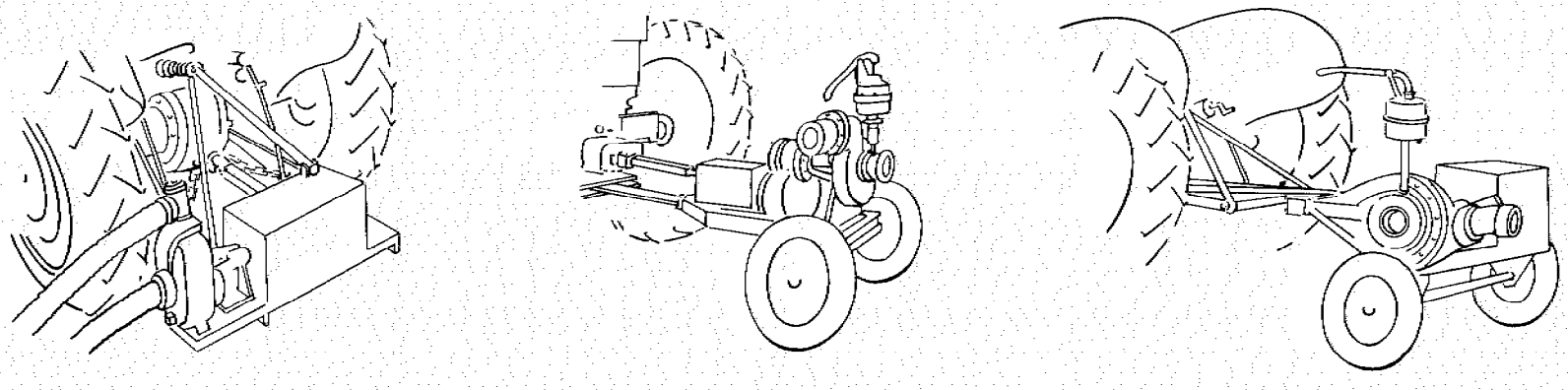


TURBINE TYPE IRRIGATION PUMP WITH GEAR HEAD CONNECTED TO A POWER UNIT WITH A SHAFT AND DOUBLE UNIVERSAL JOINT



TURBINE PUMP GEAR HEAD WITH EITHER V-BELT OR FLAT-BELT DRIVE PULLEY

Figure 8-26.--Examples of right-angle gear head drives.

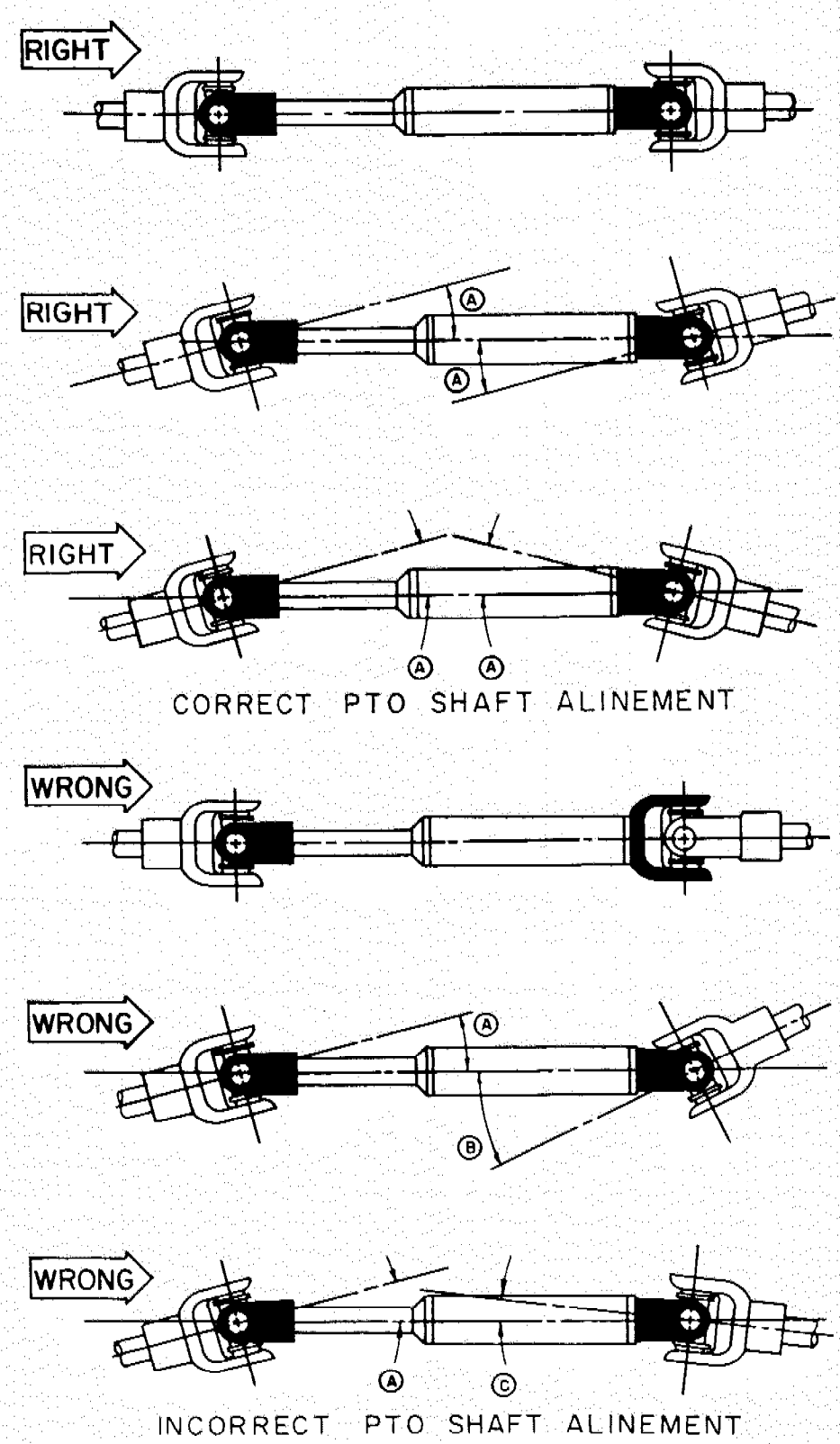


DRAWBAR MOUNTED P T O DRIVEN PUMP WITH BEVEL GEAR TYPE SPEED INCREASER

TRAILER MOUNTED P T O DRIVEN PUMP WITH SPUR GEAR TYPE SPEED INCREASER

TRAILER MOUNTED P T O DRIVEN PUMP WITH BEVEL GEAR TYPE SPEED INCREASER

Figure 8-27.--Examples of power-takeoff drives.



Sketches from Michigan State University — Extension Bulletin 338

Figure 8-28.--Correct and incorrect power-takeoff shaft alinement.

below the vapor pressure corresponding to the temperature of the liquid, the liquid will vaporize and the flowing stream will consist of liquid plus pockets of vapor. Flowing further through the impeller, the liquid reaches a region of higher pressure and the cavities of vapor collapse. It is this collapse of vapor pockets that causes the noise incident to cavitation.

Cavitation need not be a problem in a pump installation if the pump is properly designed and installed, and operated in accordance with the designer's recommendations. Also, cavitation is not necessarily destructive. Cavitation varies from very mild to very severe. A pump can operate rather noiselessly yet be cavitating mildly. The only effect may be a slight drop in efficiency. On the other hand, severe cavitation will be very noisy and will destroy the pump impeller and/or other parts of the pump.

Any pump can be made to cavitate, so care should be taken in selecting the pump and planning the installation. For centrifugal pumps, avoid as much as possible the following conditions:

1. Heads much lower than head at peak efficiency of pump.

2. Capacity much higher than capacity at peak efficiency of pump.

3. Suction lift higher or positive head lower than that recommended by manufacturer.

4. Liquid temperatures higher than that for which the system was originally designed.

5. Speeds higher than manufacturer's recommendation.

The explanation of cavitation in centrifugal pumps cannot be used when dealing with propeller pumps. The water entering a propeller pump in a large bell-mouth inlet will be guided to the smallest section, called throat, immediately ahead of the propeller. The velocity there should not be excessive and should provide a sufficiently large capacity to fill properly the ports between the propeller blades. As the propeller blades are widely spaced, not much guidance can be given to the stream of water. When the head is increased beyond a safe limit, the capacity is reduced to a quantity insufficient to fill up the space between the propeller vanes. The stream of water will separate from the propeller vanes, creating a small space where pressure is close to a perfect vacuum. In a fraction of a second, this small vacuum space will be smashed by the liquid hitting the smooth surface of the propeller vane with an enormous force which starts the process of surface pitting of the vane. At the same time one will hear a sound like rocks thrown around in a barrel or a mountain stream tumbling boulders.

The five rules applying to centrifugal pumps will be changed to suit propeller pumps in the following way. Avoid as much as possible:

1. Heads much higher than at peak efficiency of pump.

2. Capacity much lower than capacity at peak efficiency of pump.

3. Suction lift higher or positive head lower than that recommended by manufacturer.

4. Liquid temperatures higher than that for which the system was originally designed.

5. Speeds higher than manufacturer's recommendation.

Cavitation is not confined to pumping equipment alone. It also occurs in piping systems and is commonly known as water hammer.

Water hammer or hydraulic shock occurs when water flowing through a pipe undergoes a sudden change in velocity. The kinetic energy of the flowing liquid, under this latter condition, is converted into a dynamic pressure wave which may produce terrific impact in rebounding back and forth in the main. For this reason, check valves or surge pipes should be installed to protect the pump and prevent rupture of the pipe when the direction of the flow is reversed.

Water hammer sometimes reaches destructive magnitudes, especially in long pipes. It has been found to occur[2/]:

1. In starting or stopping a pump, or in an abrupt change in the pump's speed.

2. In the case of a power failure.

3. In the rapid closing of a valve in the piping system.

Destructive water hammer must be eliminated:

1. To reduce stress on the pipes and fixtures and thus minimize costly repairs, leaks, and delays.

2. To prevent reversal of pump, which may be dangerous to the motor or engine, or which may result in an unnecessary loss of liquid.

Booster Pumps

A saving in operating costs can sometimes be made in sprinkler irrigation by using a booster pump to provide adequate pressure for small areas that lie at elevations considerably above the principal area to be irrigated. The use of the booster pump for these small areas will permit the design of the main part of the irrigation system to carry lower pressures than that required for the small higher areas.

[2/] See footnote 1, p. 8-47.

The characteristics of the horizontal centrifugal pump are such that it can be used as a booster. When the centrifugal pump is operated with a positive pressure head applied to its suction, it will utilize this pressure. For example, if a pump capable of delivering 150-foot head and the water reaches the pump under a positive head or pressure of 70 feet, the pressure or head developed at the discharge will be (150 + 70) 220 feet. Therefore, two or more pumps of similar capacity can be operated, one discharging into the other to develop a total head which is the sum of the head developed by the individual pumps.

Power for Pumping

General.
Most irrigation pumps are powered by either electric motors or internal combustion engines. The source of power that is best suited for a specific installation depends on certain physical and environmental factors. The power-unit selection should be made only after considering the following:

1. The amount of brake horsepower required for pumping.

2. Hours of operation per season.

3. Availability and cost of energy or fuel. (In case of electricity, availability of single-phase or three-phase power may influence selection.)

4. Depreciation.

5. Portability desired in pumping setup.

6. Possibility of using the power unit for other jobs during the nonirrigating season.

7. Labor problems and need for convenience of operation.

8. Coldweather operation.

9. Original investment for power units.

It is highly important to match the engine horsepower to the requirements of the pump. Efficiency is sacrificed with both electric and internal combustion engines if the power plant is designed to deliver a great excess of power above the actual needs. Previously used power units should be carefully checked and evaluated as to condition, available horsepower, and speed. The efficiency of a unit in only fair mechanical condition may not exceed 50 percent. The use of an old, misfit power unit can be more costly from an operating standpoint than the most expensive unit fitted for the job.

Electric Motors.
An electric motor, properly selected and protected, can be expected to supply many years of trouble-free power if protections are provided including dry mountings, rodent protection, good ventilation, adequate

shelter from the elements, and safety devices against overloading, undervoltage, or excessive heating. Advantages of the electric power are relatively long life of the motor, low maintenance costs, dependability, and ease of operation. An electric motor also will deliver full power throughout its life and can be operated from no load to full load without damage.

Some of the disadvantages of electric power are the limited size motors which can be used when only single-phase current is available, power interruptions, and the necessity of constructing an electric supply line to all pumping locations. In some areas, phase converters are used to partially overcome the disadvantage of single-phase current.

The best type of electric motor for irrigation pumping is the 60-cycle, 220-440-volt, 3-phase, squirrel-cage induction motor. The common speeds are 860, 1,160, and 1,760 r. p. m., with the 1,760 speed being most commonly used. Single-phase motors are usually limited to loads up to 7-1/2 horsepower and, therefore, can be used only on very small pumping jobs. Standard motor sizes are 5, 7-1/2, 10, 15, 20, 25, 30, 40, 50, 60, 75, 100, 125, 150, 175, 200, 225, 250 and 300 horsepower.

An electric motor operates at constant speed. The speed of the pump must be changed either by the use of a belt drive and changing pulley diameters, or by a gear drive with a selection of gear ratios for changing speeds. When the pump and motor are directly connected, a pump must be selected that will operate acceptably at the motor speed. When it is necessary to lower the rate of pumping below that of the design rate, the speed of the pump must be reduced or the head increased by using a valve in the discharge line. On direct-connected units, valves must be used for this purpose. Direct connection between electric motor and pump should be used whenever possible because this type of connection eliminates drive loss and the added expense of the pump head.

Vertical, hollow-shaft motors are available for deep-well turbine pumps. These motors are equipped with a top cap to facilitate propeller adjustments. Two types of couplings are available for turbine pumps depending upon the method of lubrication. A nonreverse coupling is recommended when the pump has water-lubricated line shaft bearings which might possibly be damaged if the shaft were turning when there was no water surrounding the bearings. This condition occurs when the motor is stopped and the water in the well column and discharge line drains back through the pump propellers causing the pump to rotate in the reverse direction. The selfrelease coupling is used when backspin upon shutdown is not objectionable and is normally used on pumps having oil-lubricated line shaft bearings.

The brake horsepower of electric motors is rated at 100-percent continuous operation; that is, the calculated brake horsepower for a given job is the size of motor needed. Electric motors have a built-in service factor of 10 to 15 percent based upon air temperature at 70° F., standard voltage, and a free flow of air around the motor. The service factor allows the motor to operate without harm under

varying conditions of voltage and temperature. Therefore, the added horsepower provided by the service factor should not be used to arrive at a motor rating. Some of the reasons are:

1. Often on rural lines the voltages of the three phases will not always be the same. A relatively small unbalance in phase voltage will cause considerable increase in motor temperature rise. A 3-1/2-percent unbalance will cause about 25-percent increase in temperature rise.

2. Many times, particularly on rural lines, the voltage will drop below the standard. A 10-percent reduction in voltage increases the temperature rise 16 percent.

3. In many cases the methods used to determine the actual motor loads of the driven equipment are not too accurate.

4. Even with good ventilation, motor windings and cooling ducts may become covered with dust, dirt, and grease which cut down the motor's effectiveness in dissipating its heat.

5. Irrigation pumping is often required when temperatures are above 72° F.

Some means must be provided for starting electric motors. Motors require two to three times more current to start than when running. Across-the-line starting or full voltage starter means the switch is closed in one operation and one line surge is created. Reduced-voltage starting is a means of allowing the motor to start under increments of power and divides the line surge into several surges. The power supplier will advise the purchaser on the type of starter required as conditions and policies vary between locations and suppliers.

Controls should be provided to protect the motor from overload and variations occurring in the power source. Each line of three-phase power should have an automatic motor protection built into the motor control. Protective devices must be sized to the motor and load and shielded from high temperatures or sun. Sprinkler systems powered by electric motors should be equipped with a main-line flow control valve. This permits controlling line pressures and prevents overloading of motor during filling of sprinkler-distribution systems. Other types of controls are available for electric motors. Time clocks may be used to turn the pump on and off. Controls, such as time delay fuses, are available to turn the pump on after a power failure. Alarms, light indicators, and other devices are available to warn the operator if the flow of water ceases. Fuses or breakers should be used to protect the wiring and the controls.

The pump and motor should be protected from the weather. This can be accomplished by housing them in a small shed with doors and windows that can be opened to provide good cross-ventilation. The openings in the shed should be so arranged that the hot sun will not shine

directly on the controls or motor. New style vertical motors may be used without housing. The wiring and controls, however, must be weatherproofed or be in a weatherproof enclosure. The motor itself should be protected from rodents. This can be done by installing screen over air openings in the motor. The screen should have a mesh small enough to keep out mice, but not restrict the airflow. With correct protection and care, the electric motor requires little or no maintenance other than the necessary oiling or greasing required by the manufacturer.

Stationary Internal Combustion Engines.
The two general types of internal combustion engines are the spark ignition, or all engines in which combustion takes place when the fuel-air mixture is ignited by an electric spark, and the compression ignition engine better known as a Diesel. The spark-ignition engine may be either liquid-cooled or air-cooled. The air-cooled engine is becoming quite popular for direct-connected centrifugal irrigation pumps in sizes of 25 or lower continuous horsepower. The liquid-cooled engine is manufactured in all sizes. It has the advantage of automatically varying the amount of cooling to cover all possible combinations of loads and speed without over or undercooling the engine. The Diesel engine is much more costly than the spark-ignited type. However, fuel costs are much lower. The Diesel engine is seldom used when the hours of operation per season are under 800.

Manufacturers have developed performance curves for each of their engines. These curves show horsepower rating at various speeds and are used as a basis for engine selection. When the engine manufacturer conducts tests to determine the horsepower rating of an engine, a procedure standardized by the S. A. E. is used so that the horsepower curve of the various sizes and makes of engines may be compared. The test is run under laboratory conditions with a stripped engine, and the power delivered at the flywheel is determined by means of a pony brake or dynamometer. In stripping the engine for the test, accessories and equipment, such as cooling fans, generators, air cleaners and mufflers, are removed. The engine is then hooked up to the dynamometer and run under ideal conditions with the dynamometer recording the horsepower output at various operating speeds. The horsepower, as determined by the dynamometer for various operating speeds, is then plotted in the form of a curve which the manufacturer may label either "brake horsepower" or "dynamometer horsepower" (fig. 8-29).

Since the horsepower output as determined by the manufacturer's test is for laboratory conditions with a stripped engine, this curve does not represent the horsepower output of that engine with power-consuming accessories such as fans, generators, water pumps, etc. These accessories may consume as much as 10 percent of the horsepower output of the engine. The dynamometer horsepower curve must be corrected to reflect the power loss caused by the use of accessories.

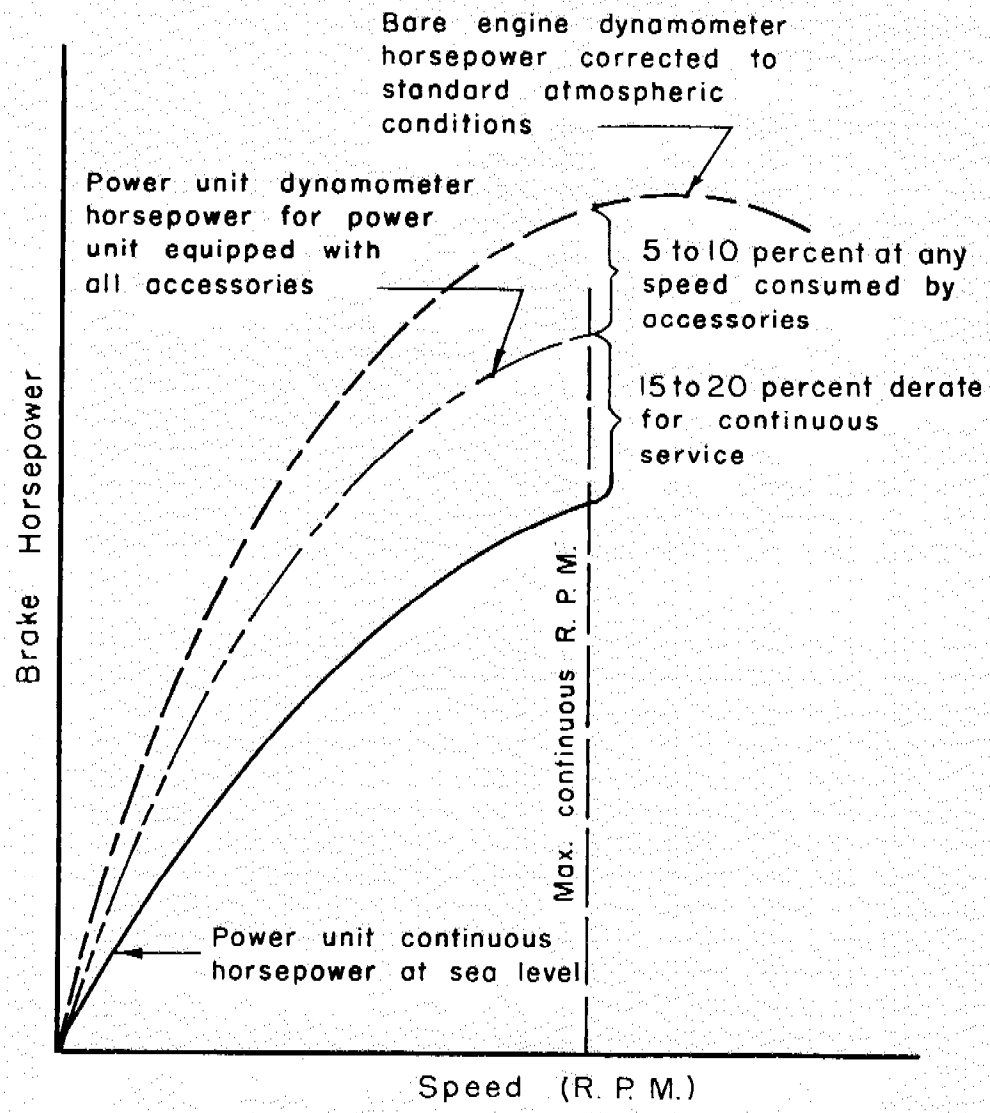


Figure 8-29.—Horsepower output of an internal combustion engine.

Because of the characteristics of the internal combustion engine, it is necessary to further correct the horsepower curve to compensate for continuous loading which is required in irrigation pumping. The effect of continuous loading will decrease the brake horsepower another 15 to 20 percent. In other words, the continuous brake horsepower output with all accessories will be 70 to 80 percent of the dynamometer horsepower as determined by laboratory test. Because altitude and air temperature affect horsepower output and laboratory tests are based on sea level and 60° temperature, it will generally be necessary to make corrections for most irrigation pumping installations. General rules for correcting for elevation and temperature are:

1. Reduce continuous load rating 3 percent for every 1,000 feet above sea level.

2. Reduce continuous load rating 1 percent for every 10° F. above 60° F.

Some manufacturers publish both the dynamometer curve and the continuous brake horsepower curve in their literature. However, when there is only one curve shown, that curve will generally be the horsepower determined by a dynamometer under laboratory conditions.

The University of Nebraska Tractor Testing Department bulletins are another source of reliable information on power output and fuel consumption for a number of gasoline and Diesel engines.

The best operating load for an internal combustion engine is at or near the continuous brake horsepower curve. Running an engine under lighter loads usually results in poor fuel economy for the water delivered, since too much horsepower is used in overcoming engine friction and throttling losses. Running at wide-open throttle invites engine trouble as well as excessive fuel consumption. The main object in irrigation pumping is to pump as much water as possible for the fuel used, and operating the engine near its highest possible load on an economy fuel mixture is the best way to accomplish this.

Irrigation pumping plants operate long periods without supervision. Therefore, safety controls should always be installed to protect the engine and pump. The power unit should have oil pressure and water temperature ignition cutoff switches which automatically shut the engine off if the oil pressure drops or the coolant temperature becomes excessive. A pump water pressure switch should also be used to protect against loss of prime or a drop in the discharge pressure head. Many manufacturers use velocity or mechanical governors to prevent overspeeding the units since the engine usually has more horsepower than the pump requires at greatest speed. Simple and inexpensive overspeed cutout switches have become available, and they replace some governors. The overspeed cutout does not absorb

any measurable power, thus offering a further advantage over governors.

Liquid-cooled engines can be cooled by either a radiator or a heat exchanger. Usually the radiator is more expensive than the heat exchanger, and it also penalizes the engine output because a fan is required. Replacing the radiator with a heat exchanger will give up to 8 percent more usable horsepower. Figure 8-14 shows an example of a heat exchanger and how it is attached to the pump discharge pipe and engine. The capacity of the heat exchanger must be sized to the engine for satisfactory results. There should never be too much cooling capacity for the engine, just as there should never be too little cooling capacity. If the engine has no thermostat, overcooling will result in excessive sludge formation and subsequent wear. If there is a thermostat, the waterflow through the block will be restricted and hot spots may develop. The manufacturer's recommendation on engine temperature should be followed religiously to prevent trouble from over or underheating.

Gasoline and distillate are the most commonly used fuels for spark-ignition engines. Liquid petroleum gas (LPG) and natural gas can also be used. They are easily burned and have almost no tendency to dilute the engine oil with the result that engine maintenance is reduced.

About the only disadvantages to LPG fuel are the initial cost of installation, the frequent need for facing exhaust valves and seats, and the possibility of rare batches of cheap fuel that have too high sulphur content. A storage tank is necessary for LPG, and this is somewhat expensive as it must withstand high pressures and have various safety features. However, buying in bulk further reduces fuel costs greatly. Natural gas is similar to LPG in combustion characteristics except it does not have as high an energy content. As a result, a given engine will have a lower power output when this fuel is substituted for LPG. Natural gas does not require storage facilities. However, it must be piped to the pump location. In locations where it is readily available, it is less expensive than LPG.

Tractor Power.

The farm tractor is probably the least desirable type of power for irrigation pumping. Often the tractor is needed for both pumping and farm operations at the same time. In this case, one or the other has to suffer. It is often used on small systems where irrigation is not needed continuously during the growing season. If a farm tractor is available during the irrigation season, it must be one that is in good mechanical condition and large enough to operate the pump at the required capacity without running at full throttle. The irrigation pump is a constant load machine and differs from the normal farm tractor work where the load is applied intermittently. The farm tractor's normal day-in and day-out workload is decidedly variable, and usually averages far less than the rated load. An engine large enough for a

tractor may not have sufficient power for pumping as horsepower rating of the tractor is based on intermittent operation.

The power from a farm tractor may be transmitted to the pump through either a belt drive or a power takeoff. Tractor manufacturers usually recommend 85 percent of the maximum belt horsepower output and 75 percent of the maximum drawbar horsepower for continuous operation. It must also be remembered that there are additional losses in the drive which vary with the type of drive. Losses in the belt drive were discussed in Belt Drive.

The power takeoff is the type of drive most commonly used with farm tractor power for irrigation pumping. As there is some loss through the power-takeoff shaft with speed increases, most authorities feel that it is desirable to limit the power takeoff power delivered to the irrigation pump to 75 percent of the maximum belt horsepower output. This maximum of 75 percent would apply only where the tractor engine is in good mechanical condition. A lower percentage should be used for older tractors, possibly dropping to 50 percent or lower for tractor motors in only fair mechanical condition.

Power Requirements

General.
To determine the actual horsepower of the power unit used in driving a pump, it is necessary to know the efficiency of the pump, the type of drive, type of power unit, the head under which the pump operates, and all losses in the piping system. The manufacturer will make guarantees on efficiencies that can be obtained for the pumps he proposes to furnish. These efficiencies can be checked in the field under actual working conditions by running a series of tests.

The efficiency of a horizontal centrifugal pump and a vertical centrifugal pump mounted in a dry well includes only the losses in the pump proper. The efficiency of a vertical submerged centrifugal pump includes the losses in the pump plus those incurred from the suction to the end of the pump discharge. The efficiency of a deep-well turbine pump includes all losses from the intake at the end of the bowls to the discharge outlet. If the power unit and pump are not directly connected, there is a "drive" loss that must be considered. These losses are well-enough established to enable accurate assumptions to be made for the various types of drives that are in common use. (Refer to Drives).

The useful work done by a pump or the water horsepower (w.hp.) required is expressed by the formula:

$$\text{w.hp.} = \frac{\text{g. p. m. x total dynamic head (t. d. h.)}}{3{,}960}$$

(The water horsepower represents the power that would be required to operate the pump if the pump and drive were 100-percent efficient.)

The brake horsepower (b.hp.) required to operate a pump is determined by the formula:

$$\text{b.hp.} = \frac{\text{water horsepower (w.hp.)}}{\text{pump efficiency x drive efficiency}}$$

$$\text{pump efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{w.hp.}}{\text{b.hp.}}$$

overall efficiency = pump efficiency x drive efficiency

Power Requirements for Electric Motors.
Electric motors are rated at 100-percent continuous operation and, therefore, the required brake horsepower to operate the pump plus losses in the drive is the size of electric motor needed.

$$\text{Required b.hp. of motor} = \frac{\text{g.p.m. x total dynamic head (t.d.h.)}}{\text{3,960 x pump eff. x drive eff.}}$$

The efficiency of an electric motor must be considered in determining power consumption. The following formulas apply:

$$\text{Kw. input to motor} = \frac{\text{b.hp. x 0.746}}{\text{motor efficiency}}$$

$$= \frac{\text{g.p.m. x t.d.h. x 0.746}}{\text{3,960 x pump eff. x drive eff. x motor eff.}}$$

$$\text{Kw. - hr. per 1,000 gals. pumped} = \frac{\text{t.d.h. x 0.00314}}{\text{pump eff. x drive eff. x motor eff.}}$$

$$\text{Kw.-hr./acre-foot} = \frac{\text{1.024 x t.d.h.}}{\text{pump eff. x drive eff. x motor eff.}}$$

Table 8-2 lists approximate efficiencies of electric motors operating at full load:

Table 8-2.--Efficiencies of electric motors operating at full speed

Horse-power	Efficiency 860 r.p.m.	Efficiency 1160 r.p.m.	Efficiency 1760 r.p.m.	Horse-power	Efficiency 860 r.p.m.	Efficiency 1160 r.p.m.	Efficiency 1760 r.p.m.
5	81	77.5	84	40	88	86.5	89.5
7 1/2	82.5	83	84	50	89	89	87.5
10	86.5	83.5	85	60	89	89.5	90
15	86	87	85	75	89	90.5	90.5
20	86	87	84	100	89	90.5	91
25	86	86	89	125	90.5	90	91
30	86	86	86	150	91	91.5	91.5
				200	91.5	91	90

Example 8-1: Given a 1,760-r.p.m. electric motor-driven pump installation with V-belt drive required to deliver 650 g.p.m. at 145 t.d.h. Pump efficiency of 75 percent and V-belt drive efficiency of 90 percent.

Find: Motor size and power consumption.

Solution: Required b.hp. of motor $= \dfrac{650 \times 145}{3{,}960 \times 0.75 \times 0.90} = 35.3$

Use a 40-hp. motor. Motor efficiency will be approximately 89.5 percent (from table 8-2).

$$\text{Input} = \frac{35.3 \times 0.746}{0.895} = 29.4 \text{ kw.}$$

$$\text{kwh./1,000 gal.} = \frac{145 \times 0.00314}{0.75 \times 0.90 \times 0.895} = 0.75$$

Power Requirements for Internal Combustion Engines.

Internal combustion engines are rated on the bare engine dynamometer hp. developed at the shaft; therefore, the efficiency of the unit does not enter into computations. The rated hp. of the engine must be in excess of the required hp. to drive the pump to offset the losses due to accessories and provide for continuous operation.

$$\text{Engine brake horsepower required to operate pump (b.hp.)} = \frac{\text{G.p.m. x t.d.h.}}{\text{3,960 x pump eff. x drive eff.}}$$

The following example shows the method of computing the brake horsepower required by an internal combustion engine to operate an irrigation pump; also, the necessary corrections for altitude, temperature, and continuous operation:

Example 8-2.

Given: Given a centrifugal pump powered by a direct drive gasoline engine to deliver 480 g. p. m. at a t. d. h. of 180 feet. Pump efficiency - 73 percent. Drive efficiency = 100 percent for direct drive. Heat exchanger used instead of engine radiator. Pumping site is 2,000 feet above sea level and the daytime temperature is 90° F.

Procedure: $$\text{B.hp.} = \frac{480 \times 180}{3960 \times 0.73 \times 1.00} = 29.9$$

Corrections for engine losses as follows:

	Loss -percent
1. Continuous load operation	20
2. Accessories -- generator, air cleaner, etc. (heat exchanger for cooling)	5
3. Elevation -- 2000 feet @ 3 percent per 1000 feet above sea level	6
4. Temperature (90° - 60° = 30° x 1 percent per 10° increase)	3
Total deduction	34

$$\text{Size of engine required} = \frac{29.9 \text{ b.hp.}}{1.0 - 0.34} = 45.3 \text{ b.hp.}$$

Cost of Pumping

General.
The engineer may be called upon to compare costs of different types of pumping installations, particularly the use of different kinds of power units. It may also be necessary to determine pumping costs in figuring the economics of irrigation. The purpose here will be to point out all factors that should be taken into consideration in computing the cost of pumping the water at the outlet of the pump.

It is impossible to give actual costs of pumping-plant installations that will be applicable to all field conditions. Close estimates of equipment and construction costs may be prepared by consultation with manufacturers and review of past installations so that the actual pumping costs will be within the limits anticipated.

Cost of pumping includes all fixed and operating costs. Fixed costs include all costs for which an initial outlay is made or a capital investment is extended, including taxes and insurance. Annual operating charges include all recurring costs.

Fixed Costs.

1. Interest. Calculated at the prevailing interest rate on the average value of the installation.

   Annual interest cost =

   $$\frac{\text{Value of installation}}{2} \times \text{interest rate}$$

2. Taxes and insurance. This item varies from one area to another. Use actual rates if available. For preliminary estimates, such costs are usually assumed to total about 1 percent of the initial cost of the installation.

3. Depreciation. Depreciation should be based on either time of operation or age. In areas where pumps are operated almost continuously, the year around hours of operation should be used. Age is a satisfactory method for determining depreciation where pumps are used less than 2,000 hours per season. Table 8-3 of depreciation figures, based on work at the University of Nebraska, can be used in figuring depreciation:

Table 8-3.---Pumping plant depreciation

Item	Estimated useful life
Well and casing	20 years
Plant housing	20 years
Pump turbine:	
Bowl (about 50 percent of cost of pump unit)	16,000 hours or 8 years
Column, etc.	32,000 hours or 16 years
Pump, centrifugal	32,000 hours or 16 years
Power transmission:	
Gear head	30,000 hours or 15 years
V-Belt	6,000 hours or 3 years
Flat-Belt, rubber and fabric	10,000 hours or 5 years
Flat-Belt, leather	20,000 hours or 10 years
Electric motor	50,000 hours or 25 years
Diesel engine	28,000 hours or 14 years
Gasoline or distillate engine:.	
Air-cooled	8,000 hours or 4 years
Water-cooled	18,000 hours or 9 years
Propane engine	28,000 hours or 14 years

Operating Costs.

1. Fuel Consumption.

a. Electric. Power consumption for electric motors can be estimated with a large degree of accuracy. The Blaney-Criddle Formula 3/ can be used as a basis for determining seasonal use. Also, studies of drought-occurrence frequencies will be helpful in determining the amount of pumping. Two methods can be used to estimate power cost:

(1) Based on number of gallons of water pumped.

Kw.-hr. per 1,000 gallons pumped =

$$\frac{\text{t.d.h.} \times 0.00314}{\text{pump eff.} \times \text{drive eff.} \times \text{motor eff.}}$$

Annual cost =

$$\frac{\text{Total No. gals. for year} \times \text{kw.-hr./1,000 gals.} \times \text{cost per kw.-hr.}}{1,000}$$

Cost per acre-inch = kw.-hr./1,000 gals. x 27.154 x cost per kw.-hr.

3/ Blaney, H. F., and W. D. Criddle. Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. U. S. Department of Agriculture, Soil Conservation Service, SCS-TP-96, 1950.

(2) Based on cost per hour for each hour that pumping system operates. For preliminary estimates, the cost per hour can be figured from table 8-4. The horsepower in the table is the required b. h. p. to operate the pump and drive and is not necessarily the size of the motor provided for the job. The figures in the table are based on a motor efficiency of 100 percent. Correct these figures according to the efficiency of the motor selected. Table 8-2 lists approximate efficiencies of electric motors based on horsepower and r. p. m.

Example 8-3:

Given: Pump installation in example 8-2. Required b.hp. = 35.3, 40 h.p. electric motor approximately 89.5 percent efficient and operating 1,200 hours per year. Power cost at $0.03 per kw.-hr.

Find: Fuel cost per hour for each hour of operation and total yearly cost.

Solution: From table 8-4, find cost per hour for 35 b.h.p. at $0.03 per kw. = $0.78 for 100 percent efficient motor. Then cost per hour for 89.5 percent efficiency = $\frac{0.78}{.895}$ = $0.87.

Total yearly cost = 1,200 x 0.87 = $1,044.

b. Internal combustion. An estimate of the rate of fuel consumption for a given engine can most accurately be made if the manufacturer's fuel-consumption curve for that engine is available. When curves are not available, the following tabulation which is based on average mechanical and operating conditions can be used for preliminary estimating purposes:

Type of engine	Fuel consumed Gallons/h.p.-hr.
Gasoline (air-cooled)	1/8
Gasoline (water-cooled)	1/10
Propane	1/7
High-speed Diesel	1/12

Fuel consumption of the propane engine probably has the greatest variance because the compression ratio has a marked effect on rate of fuel consumption. Engines with higher compression ratios consume less fuel. Any engine in poor repair may exceed the ratio given. The loads imposed on the engine is an important factor in fuel consumption. Fuel cost will go up if the throttle setting of the engine is increased beyond the manufacturer's recommendation.

(Cost per hour of operation) = b.hp. x (Fuel consumed in gallons per h.p. hour) x cost of fuel per gal.

Total annual fuel cost = Cost per hour x Total hours operated.

Fuel consumption of natural gas engines vary with the B.T.U. content of the gas. For estimating purposes, it can be assumed that 10 cubic feet of gas are required for each horsepower-hour of operation.

2. Lubricating Oil and Greases.

   a. Negligible for electric-driven plants.

   b. Internal combustion engines.

Lubricating oil		Grease per hr. of operation
Gasoline engine	1 gal. per 1,000 hp.-hrs.	$0.01
Diesel	1 gal. per 1,000 hp.-hrs.	.01
LPG and natural gas	0.3 gal. per 1,000 hp.-hrs.	.01

3. Engine maintenance and repairs. Repair costs are difficult to estimate since they tend to increase with the age of the equipment. The amount of repairs are largely affected by the total hours of operation. When accurate costs are not available, the following can be used to estimate repair and maintenance costs:

Electric motors	$3.00/year w.hp.
Gasoline and distillate	$ .00175 per w.hp-hrs.
Diesel	$ .0021 per w.hp.-hrs.

4. Pump Maintenance and Repairs.

   Turbine: Yearly cost = $\frac{\text{One-half total cost}}{\text{Estimated life in years}}$

   Centrifugal: Yearly cost = $\frac{\text{Total cost}}{\text{Estimated life in years}}$

5. Shelter Maintenance - $2.00 per year.

6. Attendance + Percent of plant operation time x Prevailing wage rate.

   The percent of plant-operation time varies according to the type of installation as follows:

Diesels with large storage tank, electric or natural gas	- 3 percent
Gasoline or distillate plants permanently mounted	- 5 percent
Movable installations	- 10 percent

Table 8-4.--Electric motor power costs 1/

Required b.hp.	Electric motor cost per hour based on 100 percent A.C. power factor and 100 percent motor efficiency when the current rate per kilowatt hour is									
	3/4	1	1½	2	2½	3	3½	4	4½	5
5	0.03	0.04	0.06	0.08	0.09	0.11	0.13	0.15	0.17	0.19
10	.06	.07	.11	.15	.19	.22	.26	.30	.34	.37
15	.08	.11	.17	.22	.28	.34	.39	.45	.50	.56
20	.11	.15	.22	.30	.37	.45	.52	.60	.67	.75
25	.14	.19	.28	.37	.47	.56	.65	.75	.39	.93
30	.17	.22	.34	.45	.56	.67	.78	.90	1.01	1.12
35	.20	.26	.39	.52	.65	.78	.91	1.04	1.18	1.31
40	.22	.30	.45	.60	.75	.90	1.04	1.19	1.34	1.49
45	.25	.34	.50	.67	.84	1.01	1.18	1.34	1.51	1.68
50	.28	.37	.56	.75	.93	1.12	1.31	1.49	1.68	1.87
60	.34	.45	.67	.90	1.12	1.34	1.57	1.79	2.01	2.24
70	.39	.52	.78	1.04	1.31	1.57	1.83	2.09	2.35	2.61
80	.45	.60	.90	1.19	1.49	1.79	2.09	2.39	2.69	2.98
90	.50	.67	1.01	1.34	1.68	2.01	2.35	2.69	3.02	3.36
100	.56	.75	1.12	1.49	1.87	2.24	2.62	2.99	3.36	3.74
120	.67	.90	1.34	1.79	2.24	2.69	3.13	3.58	4.03	4.48
140	.78	1.04	1.57	2.09	2.61	3.13	3.66	4.18	4.70	5.22
160	.90	1.19	1.79	2.39	2.98	3.58	4.18	4.77	5.37	5.97
175	.98	1.31	1.96	2.61	3.26	3.92	4.57	5.22	5.88	5.28
180	1.01	1.34	2.01	2.69	3.36	4.03	4.70	5.37	6.04	6.71
200	1.12	1.49	2.24	2.98	3.73	4.48	5.22	5.97	6.71	7.46
225	1.26	1.68	2.52	3.36	4.20	5.04	5.88	6.71	7.55	8.39
250	1.40	1.87	2.80	3.73	4.66	5.60	6.53	7.46	8.39	9.33
275	1.54	2.05	3.08	4.10	5.13	6.16	7.18	8.21	9.23	10.26
300	1.68	2.24	3.36	4.48	5.60	6.71	7.83	8.95	10.07	11.19

1/ Electric motor cost is based on the delivered horsepower, assuming an efficiency of 100 percent for the motor itself, 100 percent electrical power factor, and continuous full-load operation.

Summary.

$$\text{Total yearly costs} = \text{fixed cost} + \text{operating cost}$$

$$\text{Cost per acre-foot} = \frac{\text{total yearly cost}}{\text{acre-foot of water pumped}}$$

$$\text{Cost per acre-foot per foot of lift} = \frac{\text{cost per acre-foot}}{\text{feet of pumping lift}}$$

$$\text{Operating cost per acre-foot} = \frac{\text{operating cost}}{\text{acre-foot of water pumped}}$$

$$\text{Cost per acre} = \frac{\text{total yearly cost}}{\text{acres irrigated}}$$

Annual fixed costs depend entirely upon the amount of initial investment. In attempting to reduce these fixed costs, it is usually not a sound policy to purchase smaller equipment than needed or equipment of low quality. A smaller pumping plant that must pump the required amount of water will naturally have to operate over a longer period of time. The fixed costs by using the smaller plant would be reduced. The operating costs,however, may be increased in greater proportion. A plant of greater initial cost may be sufficiently more economical in fuel and repairs to warrant the higher fixed costs.

Only a cost study will give the information necessary to arrive at the best selection. A combination of fixed and operating costs resulting in the lowest over-all costs will generally be the best selection of the type and size of pumping plant.

Example 8-4:

Given: Six-inch centrifugal pump, flexible coupling drive; 6-cylinder industrial water-cooled gasoline engine; wooden pump house with concrete foundation; 70 acres irrigated with yearly application of 12 feet of water; 60 b.hp. required; operated 400 hours per year; total pumping head of 220 feet; gasoline at $0.25/gallon and oil at $1.00 per gallon; interest rate of 5 percent.

Find: Total yearly cost; total yearly cost per acre-foot; annual operating cost per acre-foot; and total annual cost per acre irrigated.

Solution:

1. Initial Investment.

Pump complete with suction hose and strainer	780.00
6-cylinder industrial gasoline engine	1,270.00
Pump house and foundation,.....	600.00
	$2,650.00

2. Fixed Cost — Dollars

a. Interest $\left(\frac{2650}{2} \times 0.05\right)$ 66.25

b. Taxes and insurance (2,650 x 0.01) 26.50

c. Depreciation

Centrifugal pump--- 16 years $\frac{780}{16}$ 48.75

Gasoline engine--- 9 years $\frac{1270}{9}$ 141.11

Pump house---------- 20 years $\frac{600}{20}$ 30.00

Total fixed cost $312.61

3. Annual Operating Cost

a. Fuel consumption

(Cost per hour of operation) = 60 b.hp. x 0.1 gal./hp. x $0.25/gal.= $1.50

Total annual fuel cost = $1.50 x 400 hours $600.00

b. Lubricating oil and greases

Dollars

Oil - $\frac{400 \text{ hours} \times 60 \text{ b.hp.}}{1{,}000 \text{ hours}}$ x $1.00 per gal. ... 24.00

Grease - 400 hours x $0.01 per hr. 4.00

c. Engine maintenance and repairs

$$\text{w.hp.} = \frac{800 \text{ g. p. m. x } 220 \text{ feet}}{3{,}960 \text{ w.hp.}} = 44.4$$

Cost = 44.4 w.hp. x 400 hours x $0.00175 ..... 31.08

		Dollars
d.	Pump maintenance and repairs	
	Yearly cost = $\frac{780}{16}$	48.75
e.	Shelter maintenance	2.00
f.	Attendance - 400 hours x 0.05 x $1.00 per hour	20.00
	Total annual operating cost	$729.83

4. Summary of Costs:

Total yearly cost = $312.61 + $729.83 = Dollars 1,042.44

Cost per acre-foot = $\frac{1,042.44}{1 \text{ ft.} \times 70 \text{ acres}}$ = 14.89

Cost per acre-foot per foot of lift = $\frac{14.89}{220}$ = $0.068

Operating cost per acre-foot = $\frac{729.83}{70 \text{ acres}}$ = 10.43

Total annual cost per acre = $\frac{1,042.44}{70 \text{ acres}}$ = 14.89

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Natural Resources Conservation Service

Part 623 Irrigation National Engineering Handbook

CHAPTER 9 WATER MEASUREMENT

The Natural Resources Conservation Service reference for water measurement is the United States Department of the Interior, Bureau of Reclamation publication, Water Measurement Manual, Third Edition, 1997.

The Internet location for this publication is: <http://ogee.do.usbr.gov/fmt/wmm/>

Water Measurement Manual

Contents:

Chapter 1 - Introduction
Chapter 2 - Basic Concepts Related to Flowing Water and Measurement
Chapter 3 - Measurement Accuracy
Chapter 4 - Selection of Water Measuring Devices
Chapter 5 - Inspection of Water Measurement Systems
Chapter 6 - Measuring and Recording Water Stage or Head
Chapter 7 - Wiers
Chapter 8 - Flumes
Chapter 9 - Submerged Orifices
Chapter 10 - Current Meters
Chapter 11 - Acoustic Flow Measurement
Chapter 12 - Discharge Measurements Using Tracers
Chapter 13 - Special Measurement Methods in Open Channels
Chapter 14 - Measurements in Pressure Conduits

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Section 15

Irrigation

Chapter 11

Sprinkle Irrigation

Contents

	Page
Adaptability	11-1
Advantages	11-2
Disadvantages	11-2
Types of systems	11-3
Periodic-move	11-3
Hand-move lateral	11-3
End-tow lateral	11-4
Side-roll lateral	11-4
Side-move lateral	11-5
Fixed sprinkler	11-5
Solid-set portable	11-5
Buried laterals	11-6
Gun and boom sprinklers	11-6
Continuous-move lateral	11-7
Center pivot	11-7
Traveling sprinkler	11-8
Linear-move lateral	11-9
Other sprinkle systems	11-9
Perforated pipe	11-9
Hose-fed sprinkler grid	11-9
Orchard sprinkler	11-9
Planning concepts	11-10
Preliminary design	11-10
Capacity requirements	11-11
Fixed systems	11-15
Continuous-move systems	11-16
Depth of application	11-16
Water-holding capacity	11-17
Root depth	11-17
Application depth and frequency	11-17
Intake and optimum application rates	11-18
Periodic-move and fixed systems	11-20
Continuous-move systems	11-21
Sprinkle irrigation efficiency	11-21
Uniformity	11-21
Water loss	11-23
Application	11-24
Design procedure	11-25
Periodic-move and fixed systems	11-25
Sprinkler selection	11-26
System layout	11-43
Lateral design	11-49
Mainline design	11-57
Pressure requirements	11-73
Selection of pump and power unit	11-79
Field test data	11-79
Traveling sprinkle system	11-84
Sprinkler and traveler selection	11-84
System layout	11-89
Center-pivot design	11-90
System capacity	11-90

Application intensity 11-91
Sprinkler-nozzle configuration 11-93
Lateral hydraulics 11-95
Operating pressures 11-99
Elevation-discharge relationship 11-99
Machine selection 11-101
Field test data 11-101
Linear-move system 11-109
Sprinkler-nozzle configuration 11-109
Special uses of sprinkle systems 11-110
Federal, state, and local regulations 11-110
Applying fertilizers, soil amendments, and pesticides 11-110
Fertilizer materials 11-111
Fertilizer applications 11-112
Applying soil amendments 11-112
Applying pesticides 11-112
Disposing of wastewater 11-113
Design considerations 11-113
Hardware 11-114
Frost protection 11-114
Frost control operation 11-115
Bloom delay 11-115
Microclimate control 11-116
Installation and operation of sprinkle systems 11-117
Appendix 11-118

Chapter 11

Sprinkle Irrigation

Sprinkle irrigation is the application of water in the form of a spray formed from the flow of water under pressure through small orifices or nozzles. The pressure is usually obtained by pumping, although it may be obtained by gravity if the water source is high enough above the area irrigated.

Sprinkle irrigation systems can be divided into two general categories. In periodic-move and fixed systems the sprinklers remain at a fixed position while irrigating, whereas in continuous-move systems the sprinklers operate while moving in either a circular or a straight path. The periodic-move systems include hand-move and wheel-line laterals, hose-fed sprinkler grid, perforated pipe, orchard sprinklers, and gun sprinklers. The dominant continuous-move systems are center-pivot and traveling sprinklers.

With carefully designed periodic-move and fixed systems, water can be applied uniformly at a rate based on the intake rate of the soil, thereby preventing runoff and consequent damage to land and to crops. Continuous move systems can have even higher uniformity of application than periodic-move and fixed systems, and the travel speed can be adjusted to apply light watering that reduces or eliminates runoff.

Adaptability

Sprinkle irrigation is suitable for most crops. It is also adaptable to nearly all irrigable soils since sprinklers are available in a wide range of discharge capacities. For periodic-move systems with proper spacing, water may be applied at any selected rate above 0.15 inch per hour (iph). On extremely fine-textured soils with low intake rates, particular care is required in the selection of proper nozzle size, operating pressure, and sprinkler spacing to apply water uniformly at low rates.

Periodic-move systems are well suited for irrigation in areas where the crop-soil-climate situation does not require irrigations more often than every 5 to 7 days. Light, frequent irrigations are required on soils with low water holding capacities and shallow-rooted crops. For such applications, fixed or continuously moving systems are more adaptable; however, where soil permeability is low, some of the continuously moving systems, such as the center-pivot and traveling gun, may cause runoff problems. In addition to being adaptable to all irrigation frequencies, fixed systems can also be designed and operated for frost and freeze protection, blossom delay, and crop cooling.

The flexibility of present-day sprinkle equipment, and its efficient control of water application make the method's usefulness on most topographic conditions subject only to limitations imposed by land use capability and economics.

Advantages

Some of the most important advantages of the sprinkle method are:

1. Small, continuous streams of water can be used effectively.
2. Runoff and erosion can be eliminated.
3. Problem soils with intermixed textures and profiles can be properly irrigated.
4. Shallow soils that cannot be graded without detrimental results can be irrigated without grading.
5. Steep and rolling topography can be easily irrigated.
6. Light, frequent waterings can be efficiently applied.
7. Crops germinated with sprinkler irrigation may later be surface irrigated with deeper applications.
8. Labor is used for only a short period daily in each field.
9. Mechanization and automation are practical to reduce labor.
10. Fixed systems can eliminate field labor during the irrigation season.
11. Unskilled labor can be used because decisions are made by the manager rather than by the irrigator.
12. Weather extremes can be modified by increasing humidity, cooling crops, and alleviating freezing by use of special designs.
13. Plans for intermittent irrigation to supplement erratic or deficient rainfall, or to start early grain or pasture can be made with assurance of adequate water.
14. Salts can be effectively leached from the soil.
15. High application efficiency can be achieved by a properly designed and operated system.

Disadvantages

Important disadvantages of sprinkle irrigation are:

1. High initial costs must be depreciated. For simple systems these costs, based on 1980 prices, range from $75 to $150 per acre; for mechanized and self-propelled systems, from $200 to $300; and for semi and fully automated fixed systems from $500 to $1,000.
2. Cost of pressure development, unless water is delivered to the farm under adequate pressure, is about $0.20 per acre-ft of water for each pound per square inch (psi) of pressure, based on $0.75/gal for diesel or $0.06/KWH for electricity.
3. Large flows intermittently delivered are not economical without a reservoir, and even a minor fluctuation in rate causes difficulties.
4. Sprinklers are not well adapted to soils having an intake rate of less than 0.15 inches per hour (iph).
5. Windy and excessively dry locations appreciably lower sprinkler irrigation efficiency.
6. Field shapes, other than rectangular, are not convenient to irrigate especially with mechanized sprinkle systems.
7. Cultural operations must be meshed with the irrigation cycle.
8. Surface irrigation methods on suitable soils and slopes have higher potential irrigation efficiency.
9. Water supply must be capable of being cut off at odd hours when the soil moisture deficiency is satisfied.
10. Careful management must be exercised to obtain the high potential efficiency of the method.
11. Systems must be designed by a competent specialist with full consideration for efficient irrigation, economics of pipe sizes and operation, and convenience of labor.
12. When used in overhead sprinklers, irrigation water that has high concentrations of bicarbonates may affect the quality of fruit.
13. Saline water may cause problems because salt may be absorbed by the leaves of some crops.

Sprinkle irrigation can be adapted to most climatic conditions where irrigated agriculture is feasible. Extremely high temperatures and wind velocities, however, present problems in some areas, especially where irrigation water contains large amounts of dissolved salts.

Crops such as grapes, citrus, and most tree crops are sensitive to relatively low concentrations of sodium and chloride and, under low humidity conditions, may absorb toxic amounts of these salts from sprinkle-applied water falling on the leaves. Because water evaporates between rotations of the sprinklers, salts concentrate more during this alternate wetting and drying cycle than if sprayed continuously. Plants may be damaged when these salts are absorbed. Toxicity shows as a leaf burn (necrosis) on the outer leaf-edge and can be confirmed by leaf analysis. Such injury sometimes occurs when the sodium concentration in the irrigation wa-

ter exceeds 70 ppm or the chloride concentration exceeds 105 ppm. Irrigating during periods of high humidity, as at night, often greatly reduces or eliminates this problem.

Annual and forage crops, for the most part, are not sensitive to low levels of sodium and chloride. Recent research indicates, however, that they may be more sensitive to salts taken up through the leaf during sprinkling than to similar water salinities applied by surface or trickle methods. Under extremely high evaporative conditions, some damage has been reported for more tolerant crops such as alfalfa when sprinkled with water having an electrical conductivity (EC_w) = 1.3 mmhos/cm and containing 140 ppm sodium and 245 ppm chloride. In contrast, little or no damage has occurred from the use of waters having an EC_w as high as 4.0 mmhos/cm and respective sodium and chloride concentrations of 550 and 1,295 ppm when evaporation is low. Several vegetable crops have been tested and found fairly insensitive to foliar effects at very high salt concentrations in the semi-arid areas of California. In general, local experience will provide guidelines to a crop's salt tolerance.

Damage can occur from spray of poor quality water drifting downwind from sprinkler laterals. Therefore, for periodic-move systems in arid climates where saline waters are being used, the laterals should be moved downwind for each successive set. Thus, the salts accumulated from the drift will be washed off the leaves. Sprinkler heads that rotate at 1 revolution per minute (rpm) or faster are also recommended under such conditions.

If overhead sprinklers must be used, it may not be possible to grow certain sensitive crops such as beans or grapes. A change to another irrigation method such as furrow, flood, basin, or trickle may be necessary. Under-tree sprinklers have been used in some cases, but lower leaves, if wetted, may still show symptoms due to foliar absorption.

The same guidelines used for furrow and border irrigation should also be used for sprinkle irrigation when determining allowable levels of soil salinity and leaching requirements for various crops, water qualities, and soils.

Types of Systems

There are 10 major types of sprinkle systems and several versions of each type. The major types of periodic move systems are hand-move, end-tow, and side-roll laterals; side-move laterals with or without trail lines; and gun and boom sprinklers. Fixed systems use either small or gun sprinklers. The major types of continuous-move systems are center-pivots, traveling gun or boom sprinklers, and linear-move.

Periodic-Move

Hand-Move Lateral

The hand-move portable lateral system is composed of either portable or buried mainline pipe with valve outlets at various spacings for the portable laterals. These laterals are of aluminum tubing with quick couplers and have either center-mounted or end-mounted riser pipes with sprinkler heads. This system is used to irrigate more area than any other system, and it is used on almost all crops and on all types of topography. A disadvantage of the system is its high labor requirement. This system is the basis from which all of the mechanized systems were developed. Figure 11-1 shows a typical hand-move sprinkler lateral in operation.

To reduce the need for labor the hand-move system can be modified by the addition of a tee to each sprinkler riser that is used to connect a 50-ft, 1-in-diameter, trailer pipeline with a stabilizer and another riser with a sprinkler head at the end. This modification reduces the number of hand-move laterals by half; however, the system is more difficult to move than the conventional hand-move lateral.

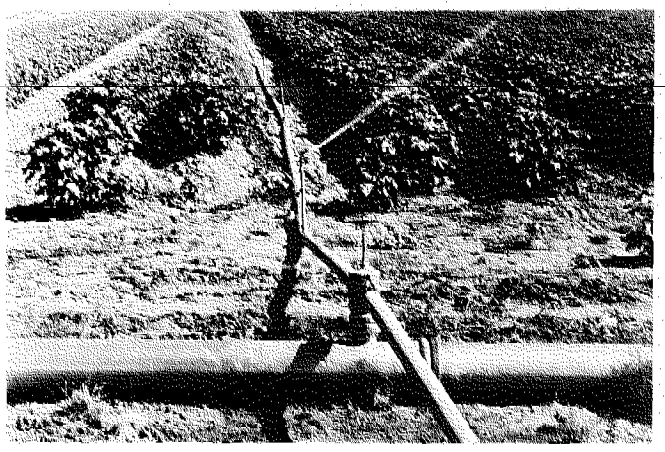


Figure 11-1.—Hand-move sprinkler lateral in operation.

End-Tow Lateral

An end-tow lateral system is similar to one with hand-move laterals except the system consists of rigidly coupled lateral pipe connected to a mainline. The mainline should be buried and positioned in the center of the field for convenient operation. Laterals are towed lengthwise over the mainline from one side to the other (fig. 11-2). By draining the pipe through automatic quick drain valves, a 20- to 30-horsepower tractor can easily pull a quarter-mile 4-inch-diameter lateral.

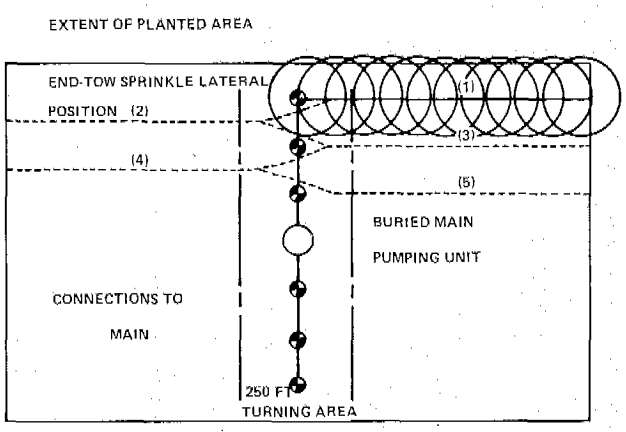


Figure 11-2—Schematic of move sequence for end-tow.

Two carriage types are available for end-tow systems. One is a skid plate attached to each coupler to slightly raise the pipe off the soil, protect the quick drain valve, and provide a wear surface when towing the pipe. Two or three outriggers are required on a quarter mile lateral to keep the sprinklers upright. The other type uses small metal wheels at or midway between each coupler to allow easy towing on sandy soils.

End-tow laterals are the least expensive mechanical move systems; however, they are not well adapted to small or irregular areas, steep or rough topography, row crops planted on the contour, or fields with physical obstructions. They work well in grasses, legumes, and other close-growing crops and fairly well in row crops, but the laterals can be easily damaged by careless operation such as moving them before they have drained, making too sharp an "S" turn, or moving them too fast. They are not, therefore, recommended for projects where the quality of the labor is undependable.

When used in row crops, a 200- to 250-ft-wide turning area is required along the length of the mainline (fig. 11-2). The turning area can be planted in alfalfa or grass. Crop damage in the turning areas can be minimized by making an offset equal to one-half the distance between lateral positions each time the lateral is towed across the mainline (fig. 11-2) instead of a full offset every other time. Irrigating a tall crop such as corn requires a special crop planting arrangement such as 16 rows of corn followed by 4 rows of a low growing crop that the tractor can drive over without causing much damage.

Side-Roll Lateral

A side-roll lateral system is similar to a system with hand-move laterals. The lateral pipes are rigidly coupled together, and each pipe section is supported by a large wheel (fig. 11-3). The lateral line forms the axle for the wheels, and when it is twisted the line rolls sideways. This unit is moved mechanically by an engine mounted at the center of the line, or by an outside power source at one end of the line.

Side-roll laterals work well in low growing crops. They are best adapted to rectangular fields with fairly uniform topography and with no physical obstructions. The diameter of the wheels should be selected so that the lateral clears the crop and so that the specified lateral move distance is a whole number of rotations of the line, e.g., for a 60-ft move use 3 rotations of a 76.4-in-diameter wheel.

Figure 11-3.—Side-roll sprinkler lateral in operation.

Side-roll laterals up to 1,600 ft long are satisfactory for use on close-planted crops and smooth topography. For rough or steep topography and for row crops with deep furrows, such as potatoes, laterals up to one-fourth mile long are recommended. Typically, 4- or 5-in-diameter aluminum tubing is used. For a standard quarter-mile lateral on a close-spaced crop at least 3 lengths of pipe to either side of a center power unit should be 0.072-in heavy walled aluminum tubing. For longer lines and in deep-furrowed row crops or on steep topography more heavy walled tubing should be used, enabling the laterals to roll more smoothly and uniformly and with less chance of breaking.

A well designed side-roll lateral should have quick drains at each coupler. All sprinklers should be provided with a self leveler so that regardless of the position at which the lateral pipe is stopped each sprinkler will be upright. In addition the lateral should be provided with at least two wind braces, one on either side of the power mover, and with a flexible or telescoping section to connect the lateral to the mainline hydrant valves.

Trail tubes or tag lines are sometimes added to heavy walled 5-in side-roll lines. With sprinklers mounted along the trail tubes the system has the capacity to irrigate more land than the conventional side-roll laterals. Special couplers with a rotating section are needed so the lateral can be rolled forward. Quick couplers are also required at the end of each trail tube so they can be detached when a lateral reaches its last operating position. The lateral must be rolled back to the starting location where the trail tubes are, then reattached for the beginning of a new irrigation cycle.

Side-Move Lateral

Side-move laterals are moved periodically across the field in a manner similar to side-roll laterals. An important difference is that the pipeline is carried above the wheels on small "A" frames instead of serving as the axle. Typically, the pipe is carried 5 ft above the ground and the wheel carriages are spaced 50 ft apart. A trail tube with 11 sprinklers mounted at 30-ft intervals is pulled behind each wheel carriage. Thus, the system wets a strip 320 ft wide, allowing a quarter-mile long line to irrigate approximately 11 acres at a setting. This system produces high uniformity and low application rates.

Side-move lateral systems are suitable for most field and vegetable crops. For field corn, however, the trail tubes cannot be used, and the "A" frames must be extended to provide a minimum ground clearance of 7 ft. Small (60 to 100 gpm) gun sprinklers mounted at every other carriage will irrigate a 150-ft-wide strip, and a quarter-mile-long lateral can irrigate 4.5 acres per setting. Application rates, however, are relatively high (approximately 0.5 iph).

The job of moving a hand-move system requires more than twice the amount of time per irrigated acre and is not nearly as easy as the job of moving an end-tow, side-roll, or side-move system. A major inconvenience of these mechanical move systems occurs, however, when the laterals reach the end of an irrigation cycle. When this happens with a hand-move system, the laterals at the field boundaries can be disassembled, loaded on a trailer, and hauled to the starting position at the opposite boundary. Unfortunately, the mechanical move laterals cannot be readily disassembled; therefore, each one must be deadheaded back to its starting position. This operation is quite time consuming, especially where trail tubes are involved.

Fixed Sprinkler

A fixed-sprinkler system has enough lateral pipe and sprinkler heads so that none of the laterals need to be moved for irrigation purposes after being placed in the field. Thus to irrigate the field the sprinklers only need to be cycled on and off. The three main types of fixed systems are those with solid-set portable hand-move laterals (fig. 11–4), buried or permanent laterals, and sequencing valve laterals. Most fixed sprinkler systems have small sprinklers spaced 30 to 80 ft apart, but some systems use small gun sprinklers spaced 100 to 160 ft apart.

Solid-Set Portable

Solid-set portable systems are used for potatoes and other high-value crops where the system can be moved from field to field as the crop rotation or irrigation plan for the farm is changed. These systems are also moved from field to field to germinate such crops as lettuce, which are then furrow irrigated. Moving the laterals into and out of the field requires much labor, although this requirement can be reduced by the use of special trailers on which the portable lateral pipe can be stacked by hand. After a trailer has been properly loaded, the pipe is banded in several places to form a bundle that is lifted off the trailer at the farm storage yard with a

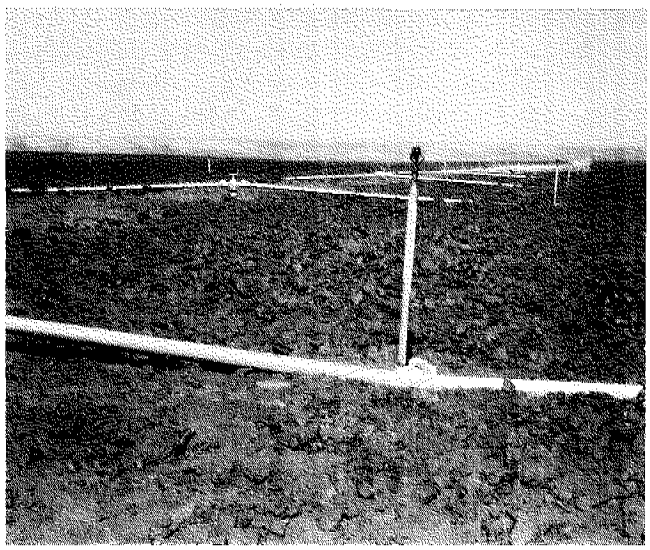


Figure 11-4.—Solid-set sprinkler laterals connected to buried mainline.

mechanical lifter. The procedure is reversed when returning the laterals to the field for the next season.

Buried Laterals

Permanent, buried laterals are placed underground 18 to 30 inches deep with only the riser pipe and sprinkler head above the surface. Many systems of this type are used in citrus groves, orchards, and field crops.

The sequencing valve lateral may be buried, laid on the soil surface, or suspended on cables above the crop. The heart of the system is a valve on each sprinkler riser that turns the sprinkler on or off when a control signal is applied. Most systems use a pressure change in the water supply to activate the valves.

The portable lateral, buried or permanent lateral, and sequencing valve lateral systems can be automated by the use of electric or air valves activated by controllers. These automatic controllers can be programmed for irrigation, crop cooling, and frost control and can be activated by soil moisture measuring and temperature sensing devices.

Gun and Boom Sprinklers

Gun (or giant) sprinklers have 5/8-in or larger nozzles attached to long (12 or more inches) discharge tubes. Most gun sprinklers are rotated by means of a "rocker arm drive" and many can be set to irrigate a part circle (fig. 11-5).

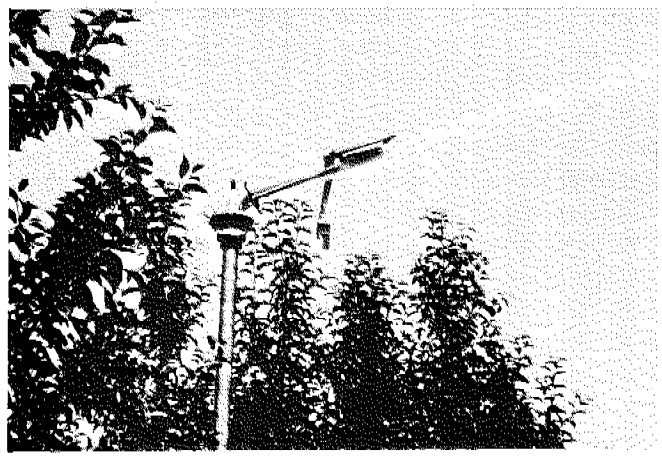


Figure 11-5.—Part circle gun sprinkler with rocker arm drive in operation.

Boom sprinklers have a rotating 110- to 250-ft boom supported in the middle by a tower mounted on a trailer. The tower serves as the pivot for the boom that is rotated once every 1 to 5 minutes by jets of water discharged from nozzles. The nozzles are spaced and sized to apply a fairly uniform application of water to a circular area over 300 ft in diameter (fig. 11-6).

Gun or boom sprinkler systems can be used in many similar situations and are well adapted to supplemental irrigation and for use on irregularly shaped fields with obstructions. Each has its comparative advantages and disadvantages. Gun sprinklers, however, are considerably less expensive and are simpler to operate; consequently, there are more gun than boom sprinklers in use. Gun and boom sprinklers usually discharge more than 100 gpm and are operated individually rather than as sprinkler-laterals. A typical sprinkler discharges 500 gpm and requires 80 to 100 psi operating pressure.

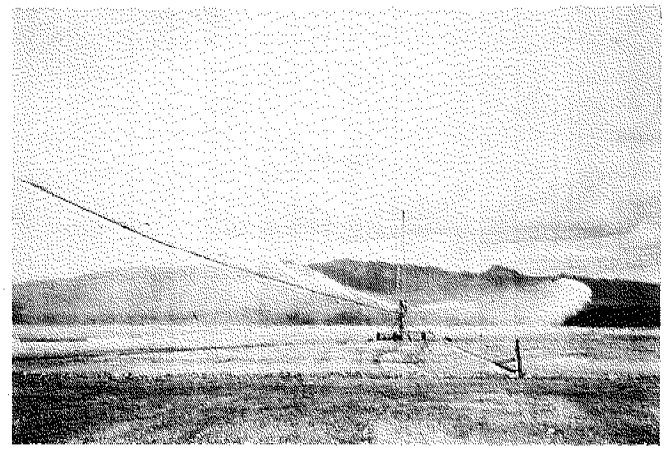


Figure 11-6.—Boom sprinkler in operation.

Gun and boom sprinklers can be used on most crops, but they produce relatively high application rates and large water drops that tend to compact the soil surface and create runoff problems. Therefore, these sprinklers are most suitable for coarse-textured soils with high infiltration rates and for relatively mature crops that need only supplemental irrigation. Gun and boom sprinklers are not recommended for use in extremely windy areas because their distribution patterns become too distorted.

Large gun sprinklers are usually trailer or skid mounted and like boom sprinklers are towed from one position to another by a tractor. Boom sprinklers are unstable and can tip over when being towed over rolling or steep topography.

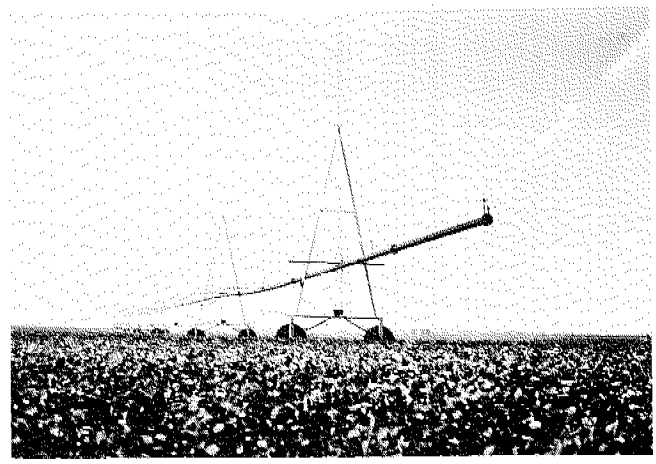


Figure 11-7.—Outer end of center-pivot lateral in operation.

Continuous-Move Lateral

Center-Pivot

The center-pivot system sprinkles water from a continuously moving lateral pipeline. The lateral is fixed at one end and rotates to irrigate a large circular area. The fixed end of the lateral, called the "pivot point," is connected to the water supply. The lateral consists of a series of spans ranging in length from 90 to 250 ft and carried about 10 ft above the ground by "drive units," which consist of an "A-frame" supported on motor driven wheels (fig. 11-7).

Devices are installed at each drive unit to keep the lateral in a line between the pivot and end-drive unit; the end-drive unit is set to control the speed of rotation. The most common center-pivot lateral uses 6-in pipe, is a quarter mile long (1,320 ft), and irrigates the circular portion (126 acres plus 2 to 10 acres more depending on the range of the end sprinklers) of a quarter section (160 acres). However, laterals as short as 220 ft and as long as a half mile are available.

The moving lateral pipeline is fitted with impact, spinner, or spray-nozzle sprinklers to spread the water evenly over the circular field. The area to be irrigated by each sprinkler set at a uniform sprinkler spacing along the lateral becomes progressively larger toward the moving end. Therefore, to provide uniform application the sprinklers must be designed to have progressively greater discharges, closer spacings, or both, toward the moving end. Typically, the application rate near the moving end is about 1.0 iph. This exceeds the intake rate of many soils except for the first few minutes at the beginning of each irrigation. To minimize surface ponding and runoff, the laterals are usually rotated every 10 to 72 hours depending on the soil's infiltration characteristics, the system's capacity, and the maximum desired soil moisture deficit.

Five types of power units commonly used to drive the wheels on center pivots are electric motors, water pistons, water spinners and turbines, hydraulic oil motors, and air pistons. The first pivots were powered by water pistons; however, electric motors are most common today because of their speed, reliability, and ability to run backwards and forwards.

Self-propelled, center-pivot sprinkler systems are suitable for almost all field crops but require fields free from any obstructions above ground such as telephone lines, electric power poles, buildings, and trees in the irrigated area. They are best adapted for use on soils having high intake rates, and on uniform topography. When used on soils with low intake rate and irregular topography, the resulting runoff causes erosion and puddles that may interfere with the uniform movement of the lateral around the pivot point. If these systems are used on square subdivisions, some means of irrigating the four corners must be provided, or other uses made of the area not irrigated. In a 160-acre quarter-section subdivision, about 30 acres are not irrigated by the center-pivot system unless the pivot is provided with a special corner irrigating apparatus. With some corner systems only about 8 acres are left unirrigated.

Most pivot systems are permamently installed in a given field. But in supplemental irrigation areas

or for dual cropping, it is practical to move a standard quarter-mile center-pivot lateral back and forth between two 130-acre fields.

Traveling Sprinkler

The traveling sprinkler, or traveler, is a high-capacity sprinkler fed with water through a flexible hose; it is mounted on a self-powered chassis and travels along a straight line while watering. The most common type of traveler used for agriculture in the United States has a giant gun-type 500-gpm sprinkler that is mounted on a moving vehicle and wets a diameter of more than 400 ft. The vehicle is equipped with a water piston or turbine-powered winch that reels in the cable. The cable guides the unit along a path as it tows a flexible high-pressure lay-flat hose that is connected to the water supply pressure system. The typical hose is 4 inches in diameter and is 660 ft. long, allowing the unit to travel 1,320 ft unattended (fig. 11-8). After use, the hose can be drained, flattened, and wound onto a reel.

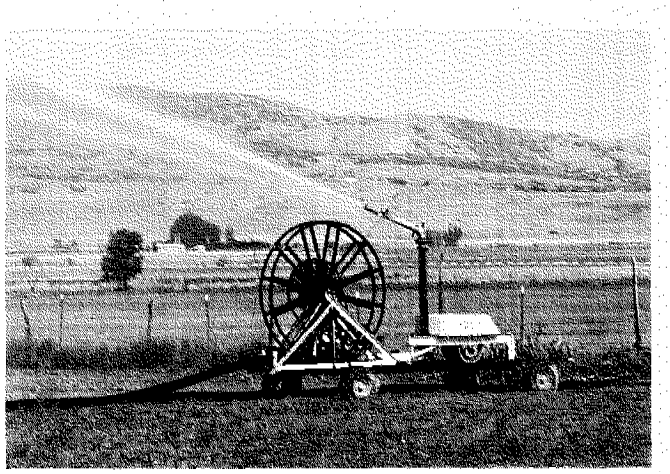


Figure 11-8.—Hose-fed traveling gun-type sprinkler in operation.

Some traveling sprinklers have a self-contained pumping plant mounted on the vehicle that pumps water directly from an open ditch while moving. The supply ditches replace the hose.

Some travelers are equipped with boom sprinklers instead of guns. Boom sprinklers have rotating arms 60 to 120 ft long from which water is discharged through nozzles as described earlier.

As the traveler moves along its path, the sprinkler wets a strip of land about 400 ft wide rather than the circular area wetted by a stationary sprinkler. After the unit reaches the end of a travel path, it is moved and set up to water an adjacent strip of land. The overlap of adjacent strips depends on the distance between travel paths and on the diameter of the area wetted by the sprinkler. Frequently a part-circle sprinkler is used; the dry part of the pattern is over the towpath so the unit travels on dry ground (fig. 11-9).

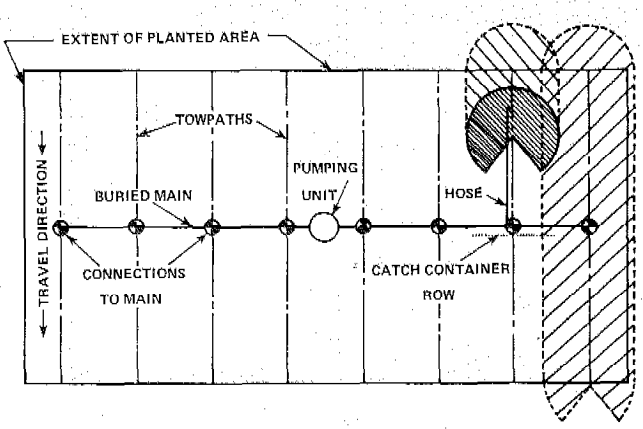


Figure 11-9.—Typical layout for traveling sprinklers showing location of the line of catch containers used for evaluating the distribution uniformity.

Figure 11-9 shows a typical traveling sprinkler layout for an 80-acre field. The entire field is irrigated from 8 towpaths each 1,320 ft long and spaced 330 ft apart.

Traveling sprinklers require the highest pressures of any system. In addition to the 80 to 100 psi required at the sprinkler nozzles, hose friction losses add another 20 to 40 psi to the required system pressure. Therefore, travelers are best suited for supplemental irrigation where seasonal irrigation requirements are small, thus mitigating the high power costs associated with high operating pressures.

Traveling sprinklers can be used in tall field crops such as corn and sugarcane and have even been used in orchards. They have many of the same advantages and disadvantages discussed under gun and boom sprinklers; however, because they are moving, traveling sprinklers have a higher uniformity and lower application rate than guns and booms. Nevertheless, the application uniformity of travelers is only fair in the central portion of the field, and 100- to 200-ft-wide strips along the ends and sides of the field are usually poorly irrigated.

Linear-Move Lateral

Self-propelled linear-move laterals combine the structure and guidance system of a center-pivot lateral with a traveling water feed system similar to that of a traveling sprinkler.

Linear-move laterals require rectangular fields free from obstructions for efficient operation. Measured water distribution from these systems has shown the highest uniformity coefficients of any system for single irrigations under windy conditions.

Systems that pump water from open ditches must be installed on nearly level fields. Even if the system is supplied by a flexible hose, the field must be fairly level in order for the guidance system to work effectively.

A major disadvantage of linear-move systems as compared to center-pivot systems is the problem of bringing the lateral back to the starting position and across both sides of the water supply line. Since the center-pivot lateral operates in a circle, it automatically ends each irrigation cycle at the beginning of the next, but because the linear-move lateral moves from one end of the field to the other it must be driven or towed back to the starting position. However, the linear-move system can irrigate all of a rectangular field, whereas the center-pivot system can irrigate only a circular portion of it.

Other Sprinkle Systems

Because of the recent concerns about availability and cost of energy, interest has revived in the use of perforated pipe, hose-fed sprinklers run on a grid pattern, and orchard systems. They afford a means of very low pressure (5 to 20 psi) sprinkle irrigation. Often, gravity pressure is sufficient to operate the system without pumps. Furthermore, inexpensive low-pressure pipe such as unreinforced concrete and thin-wall plastic or asbestos cement can be used to distribute the water. These systems do have the disadvantage of a high labor requirement when being moved periodically.

Perforated Pipe

This type of sprinkle irrigation has almost become obsolete for agricultural irrigation but continues to be widely used for home lawn systems. Perforated pipe systems spray water from 1/16-in-diameter or smaller holes drilled at uniform distances along the top and sides of a lateral pipe. The holes are sized and spaced so as to apply water uniformly between adjacent lines of perforated pipeline (fig. 11-10). Such systems can operate effectively at pressures between 5 and 30 psi, but can be used only on coarse-textured soils such as loamy sands with a high capacity for infiltration.

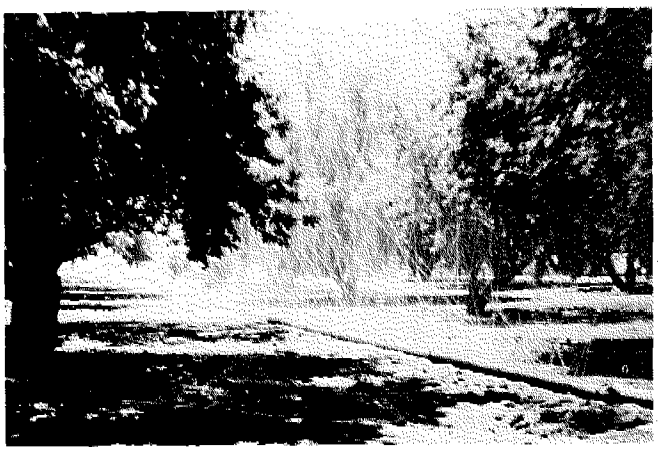


Figure 11-10.—Perforated pipe lateral in operation.

Hose-Fed Sprinkler Grid

These systems use hoses to supply individual small sprinklers that operate at pressures as low as 5 to 10 psi. They can also produce relatively uniform wetting if the sprinklers are moved in a systematic grid pattern with sufficient overlap. However, these systems are not in common use except in home gardens and turf irrigation, although they do hold promise for rather broad use on small farms in developing countries where capital and power resources are limited and labor is relatively abundant.

Orchard Sprinkler

A small spinner or impact sprinkler designed to cover the space between adjacent trees with little or no overlap between the areas wetted by neighboring sprinklers. Orchard sprinklers operate at pressures between 10 and 30 psi, and typically the diameter of coverage is between 15 and 30 ft. They are located under the tree canopies to provide approximately uniform volumes of water for each tree. Water should be applied fairly evenly to areas wetted, although some soil around each tree may receive little or no irrigation (fig. 11-11). The individual sprinklers can be supplied by hoses and periodically moved to cover several positions or a sprinkler can be provided for each position.

A complete farm sprinkle system is a system planned exclusively for a given area or farm unit on which sprinkling will be the primary method of water application. Planning for complete systems includes consideration of crops and crop rotations used, water quality, and the soils found in the specified design area.

A farm sprinkle-irrigation system includes sprinklers and related hardware; laterals, submains, mainlines; pumping plant and boosters; operation-control equipment; and other accessories required for the efficient application of water. Figure 11-12 shows a periodic-move system with buried mainlines and multiple sprinkler laterals operating in rotation around the mainlines.

Figure 11-11.—Orchard sprinkler operating from a hose line.

Large farm systems are usually made up of several field systems designed either for use on several fields of a farm unit or for movement between fields on several farm units. Field systems are planned for stated conditions, generally for preirrigation, for seed germination, or for use in specialty crops in a crop rotation. Considerations of distribution efficiency, labor utilization, and power economy may be entirely different for field systems than for complete farm systems. Field systems can be fully portable or semiportable.

Failure to recognize the fundamental difference between field and farm systems, either by the planner or the owner, has led to poorly planned systems of both kinds. In between these two is the incomplete farm system, initially used as a field system but later intended to become a part of a complete farm system.

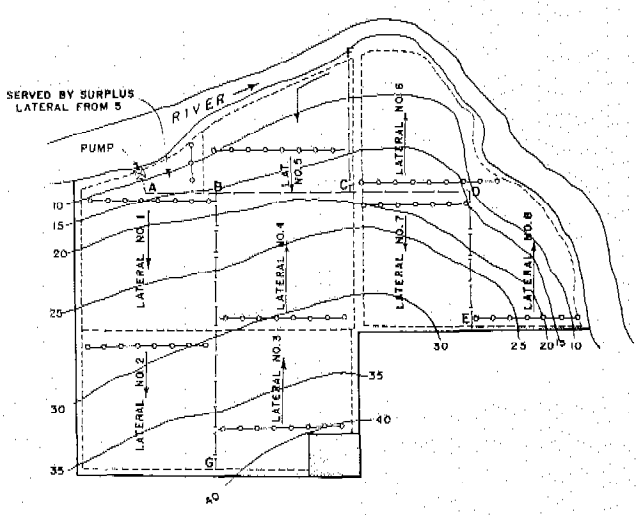


Figure 11-12.—Layout of a complete periodic hand-move sprinkle system. The odd-shaped area of 72 acres illustrates the subdivision of the design area to permit rotation to all areas except one small tract near the pumping location. Number of sprinklers required per acre, 1.5; number of settings for each lateral per irrigation, 10; required number of sprinklers, 72 × 1.5 = 108; total sprinklers required for the eight laterals, 124. Lateral 8 will require an intermediate pressure-control valve.

Failure to anticipate the capacity required of the ultimate system has led to many piecemeal systems with poor distribution efficiencies, excessive initial costs, and high annual water-application charges. This situation is not always the fault of the system planner since he may not always be informed as to whether future expansion is intended, however, he has a responsibility to inform the owner of possible considerations for future development when he prepares a field-system plan.

Preliminary Design

The first six steps of the design procedure outlined below are often referred to as the preliminary design factors. Some of these steps are discussed in more detail in other chapters.

1. Make an inventory of available resources and operating conditions. Include information on soils, topography, water supply, source of power, crops, and farm operation schedules following instructions in Chapter 3, *Planning Farm Irrigation Systems.*

2. From the local irrigation guide, determine the depth or quantity of water to be applied at each irrigation. If there is no such guide, follow instructions in Chapter 1, *Soil-Plant-Water Relations*, to compute this depth.

3. Determine from the local irrigation guide the average peak period daily consumptive use rates and the annual irrigation requirements for the crops to be grown. The needed information is available. The procedure is discussed more fully in Technical Release No. 21, *Irrigation Water Requirements*.

4. Determine from the local irrigation guide design-use frequency of irrigation or shortest irrigation period. The procedure is discussed more fully in Chapter 1. This step is often not necessary for fully automated fixed systems or for center-pivot systems.

5. Determine capacity requirements of the system as discussed in Chapter 3, *Planning Farm Irrigation Systems*.

6. Determine optimum water-application rate. Maximum (not necessarily optimum) rates are obtainable from the local irrigation guide.

7. Consider several alternative types of sprinkler systems. The landowner should be given alternatives from which to make a selection.

8. For periodic move and fixed sprinkle systems:

a. Determine sprinkler spacing, discharge, nozzle size, and operating pressure for the optimum water-application rate.

b. Estimate number of sprinklers operating simultaneously, required to meet system capacity requirements.

c. Determine the best layout of main and lateral lines for simultaneous operation of the approximate number of sprinklers required.

d. Make necessary final adjustments to meet layout conditions.

e. Determine sizes of lateral line pipe required.

f. Compute maximum total pressure required for individual lateral lines.

9. For continuous-move sprinkle systems:

a. Select the type of sprinkle nozzle desired.

b. Set the minimum allowable nozzle pressure.

c. Determine the desired system flow rate.

d. Select the type of system drive, i.e., electric, hydraulic.

e. Determine the maximum elevation differences that will be encountered throughout the movement of the system.

f. Select the system pipe (or hose) diameter based on economic considerations.

g. Calculate the system inlet pressure required to overcome friction losses and elevation differences and provide the desired minimum nozzle pressure.

10. Determine required size of mainline pipe.

11. Check mainline pipe sizes for power economy.

12. Determine maximum and minimum operating conditions.

13. Select pump and power unit for maximum operating efficiency within range of operating conditions. The selection of a pump and power plant is discussed in Chapter 8, *Irrigation Pumping Plants*.

14. Prepare plans, schedules, and instructions for proper layout and operation.

Figure 11-13 is useful for organizing the information and data developed through carrying out these steps. Section V is set up specifically for periodic-move and fixed-sprinkle systems. It can be modified slightly for continuous-move systems by replacing parts a, b, and c with:

a. Maximum application rate (iph)

b. Time per revolution (or per single run) (hr)

c. Speed of end tower (or of machine) (ft/min)

Figure 11-13 contains four columns that can be used for different crops or for different fields on the same farm.

The farmer should be consulted concerning his financial, labor, and management capabilities. Once the data on the farm's resources have been assembled the system selection, layout, and hydraulic design process can proceed.

Capacity Requirements

The required capacity of a sprinkle system depends on the size of the area irrigated (design area), the gross depth water applied at each irrigation, and the net operating time allowed to apply this depth. The capacity of a system can be computed by the formula:

$$Q = \frac{453\ Ad}{fT} \qquad (11\text{-}1)$$

Where

Q = system discharge capacity (gpm)
A = design area (acres)
d = gross depth of application (in)
f = time allowed for completion of one irrigation (days)
T = actual operating time (hr/day)

I.	Crop (Type)				
	(a) Root depth (ft)				
	(b) Growing season (days)				
	(c) Water use rate (in/day)				
	(d) Seasonal water use (in)				
II.	Soils (Area)				
	(a) Surface texture Depth (ft) Moisture capacity (in/ft)				
	(b) Subsurface texture Depth (ft) Moisture capacity (in ft)				
	(c) Mositure capacity (in)				
	(d) Allowable depletion (in)				
	(e) Intake rate (iph)				
III.	Irrigation				
	(a) Interval (days)				
	(b) Net depth (in)				
	(c) Efficiency (%)				
	(d) Gross depth (in)				
IV.	Water requirement				
	(a) Net seasonal (in)				
	(b) Effective rain (in)				
	(c) Stored moisture (in)				
	(d) Net irrigation (in)				
	(e) Gross irrigation (in)				
	(f) Number of irrigations				
V.	System capacity				
	(a) Application rate (iph)				
	(b) Time per set (hrs)				
	(c) Settings per day				
	(d) Days of operation per interval				
	(e) Preliminary system Capacity (gpm)				

Figure 11-13.—Factors for preliminary sprinkle irrigation system design.

For center-pivot systems and fully automatic fixed systems, it is best to let d equal the gross depth required per day and f = 1.0. To allow for some breakdown or moving of systems, T can be reduced by 5 to 10 percent from the potential value of 24 hr.

Of major importance are f and T because they have a direct bearing on the capital investment per acre required for equipment. From equation 1 it is obvious that the longer the operating time (fT) the smaller the required system capacity and, therefore, the cost for irrigating a given acreage. Conversely, where the farmer wishes to irrigate an acreage in a minimum number of days and has labor available only for operation during daylight hours, the equipment costs per acre will be high. With center-pivot and automated field systems, light, frequent irrigations are practical because labor requirements are minimal. With these systems irrigation frequency should be based on maintaining optimum soil-plant-water conditions rather than on allowing soil moisture depletion levels that are a compromise between labor requirements, capital costs, and growing conditions (as recommended in Chapter 1).

Before a sprinkle system is planned, the designer should thoroughly acquaint the owner with these facts and the number of operating hours that can be allowed for completing one irrigation. Also the farmer should understand the amount of labor required to run the sprinkle system so that this operation interferes minimally with other farming operations.

Areas that have several soil zones that vary widely in water-holding capacity and infiltration rate can be subdivided on the basis of the water needed at each irrigation (fig. 11-14) for all systems except center pivots. It is easier to operate center-pivot sprinklers as though the entire field has the soil with the lowest water-holding capacity and infiltration rate.

Sample calculation 11-1 has been prepared as an example of the use of the formula where a single crop is irrigated in the design area. The design moisture use rate and irrigation frequency can be obtained from irrigation guides where available. Otherwise, they may be computed from Technical Release No. 21, *Irrigation Water Requirements* and Chapter 1, *Soil-Plant-Water Relationships*.

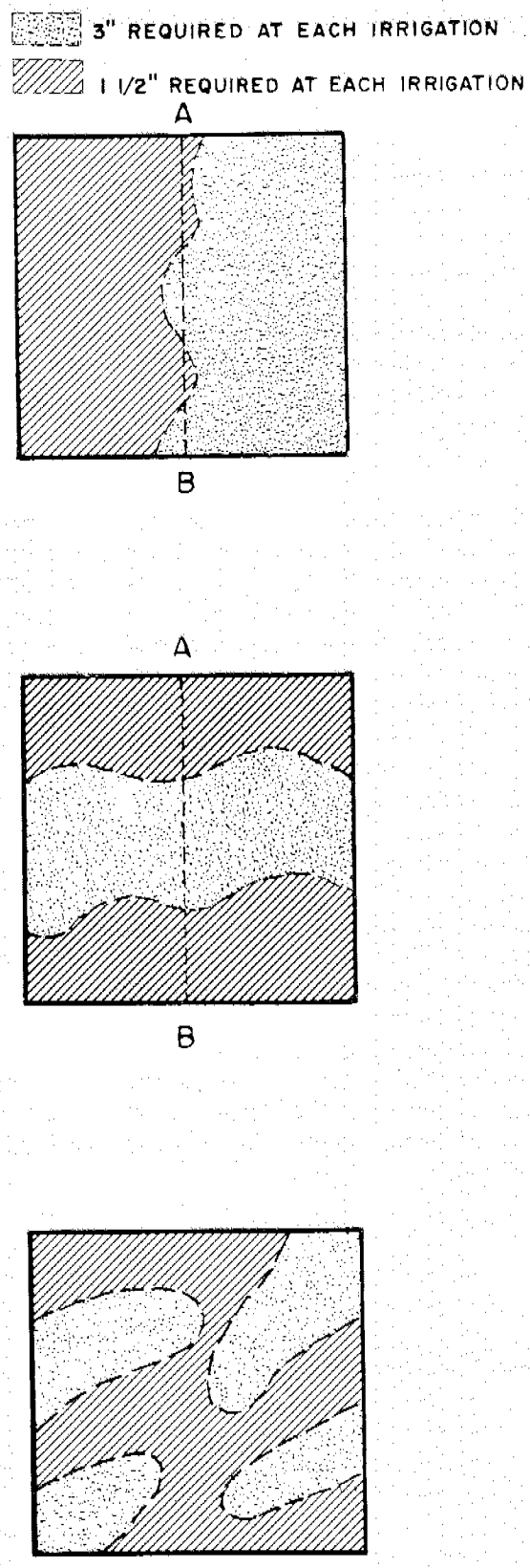


Figure 11-14.—Subdivision of design areas having different soil zones.

Sample calculation 11-1.—Computing capacity requirements for a single crop in the design area.

Given:

40 acres of corn (A)
Design moisture use rate: 0.20 in/day
Moisture replaced in soil at each irrigation: 2.4 in
Irrigation efficiency: 70%
Gross depth of water applied (d): 2.4/0.70 or 3.4 in a 70% efficiency
Irrigation period (f): 10 days in a 12-day interval
System to be operated 20 hr/day (T)
3.0 in required at each irrigation
1.5 in required at each irrigation

A The design area can be served by a mainline as indicated by the dotted line. Laterals can operate on both sides, but must run twice as long on the 3.0-in zone and twice as often on the 1.5-in zone, or else separate laterals must be designed for each zone with different water application rates. In either case the frequency of irrigation would be two times on the 1.5-in zone for each time on the 3.0-in zone.

B The system is designed for a uniform soil area using the 1.5-in water-application rate. Once during the early growing season, the lateral or laterals could be operated twice as long on the 3.0-in zone, but the entire area would be irrigated at the frequency required for the 1.5-in zone during peak-moisture-use periods.

C Again the system would be designed for the 1.5-in zone. For deep-rooted crops, the entire area might be given a 3.0-in application for the first irrigation in the spring. However, this would mean some sacrifice in water-application efficiency.

Calculation using equation 1:

$$Q = \frac{453\ Ad}{fT} = \frac{453 \times 40 \times 3.4}{10 \times 20} = 308 \text{ gpm}$$

Where two or more areas with different crops are being irrigated by the same system and peak design-use rates for the crops occur at about the same time of the year, the capacity for each area is computed as shown in sample calculation 11-1 and capacities for each area are summed to obtain the required capacity of the system. The time allotted for completing one irrigation over all areas (f) must not exceed the shortest irrigation-frequency period as shown in the local irrigation guide or determined by the procedure in Chapter 1.

System-capacity requirements for an area in a crop rotation are calculated to satisfy the period of water use. Therefore, allowances must be made for the differences in time when the peak-use requirements for each crop occur (sample calculation 11-2).

Sample calculation 11-2.—Computing capacity requirements for a crop rotation.

Given:

Design area of 90 acres with crop acreages as follows:
10 acres Irish potatoes, last irrigation May 31;
2.6-inch application lasts 12 days in May (peak period);
30 acres corn, last irrigation August 20;
2.9-inch application lasts 12 days in May;
3.4-inch application lasts 12 days in July (peak period);
50 acres alfalfa, irrigated through frost-free period;
3.6-inch application lasts 12 days in May;
4.3-inch application lasts 12 days in July (peak period);
Irrigation period is 10 days in 12-day irrigation interval;
System is to be operated 16 hr per day.
Calculations using equation 1:
Capacity requirements for May when all three crops are being irrigated.

Irish potatoes $Q = \frac{453 \times 10 \times 2.6}{10 \times 16} = 74$ gpm

Corn $Q = \frac{453 \times 30 \times 2.9}{10 \times 16} = 246$ gpm

Alfalfa $Q = \frac{453 \times 50 \times 3.6}{10 \times 16} = 510$ gpm

Total for May = 830 gpm

Capacity requirements for July when potatoes have been harvested but corn and alfalfa are using moisture at the peak rate

Corn $Q = \frac{453 \times 30 \times 3.4}{10 \times 16} = 289$ gpm

Alfalfa $Q = \frac{453 \times 50 \times 4.3}{10 \times 16} = 609$ gpm

Total for July = 898 gpm

Although only two of the three crops are being irrigated, the maximum capacity requirement of the system is in July.

The quality of most water is good enough that no extra system capacity is required for leaching during the peak use period. Leaching requirements can usually be adequately satisfied before and after the peak use-period.

If highly saline irrigation water is to be used on salt sensitive crops (when the conductivity of the irrigation water is more than half the allowable conductivity of the drainage water), it is advisable to provide a portion of the annual leaching requirement at each irrigation. Thus, the system capacity should be increased by an amount equal to the annual leaching requirement divided by the number of irrigations per year. The procedure for determining leaching requirements is presented in Technical Release No. 21.

It is not wise to irrigate under extremely windy conditions, because of poor uniformity and excessive drift and evaporation losses. This is especially true with periodic-move systems on low infiltration soils that require low application rates. When these conditions exist, system capacities must be increased proportionately to offset the reduced number of sprinkling hours per day.

In water-short areas, it is sometimes practical to purposely underirrigate to conserve water at the expense of some reduction in potential yields. Yields per unit of water applied often are optimum with system capacities about 20 percent lower than are specified for conventional periodic-move systems in the same area. Underirrigation is best achieved by using a longer interval between irrigations than is normally recommended for optimum yields.

Fixed Systems

Fixed systems can be used for ordinary irrigation, high frequency irrigation, crop cooling, and frost protection. Special consideration is required when estimating the system capacity required by each of these uses. All fixed systems are ideal for applying water-soluble fertilizers and other chemicals.

Ordinary Irrigation.—Some fixed systems are installed in permanent crops, and relatively long irrigation intervals are used. The capacity of such systems can be 5 to 10 percent less than conventional periodic-move systems in the same area because there is no down time during lateral moves. The capacity should be sufficient to apply the peak "net" crop water requirements for low frequency (1- or 2-week interval) irrigations when the system is operated on a 24-hr day, 7-day week basis. These systems may be used to apply fertilizers and other chemicals and can be controlled by hand valves.

High Frequency.—If the system is designed to apply irrigations once or twice a day to control soil temperatures and to hold the soil moisture content within a narrow band, a greater system capacity is required. The net system capacity should be increased by 10 to 20 percent over a conventional periodic-move system because the crop will always be consuming water at the peak potential evapotranspiration rate. By contrast, under lower frequency irrigation, as the soil moisture decreases the consumptive use rate falls below the peak potential rate. A major purpose for such a system is to keep the crop performing at a peak rate to increase quality and yield. Clearly, crops that do not respond favorably to uniform high soil moisture conditions are not particularly good candidates for solid set systems. High frequency systems can be hand valve operated. However, automatic valve systems can be used to apply fertilizers and chemicals.

Crop Cooling.—Very high frequency systems used for foliar cooling must have automatic valving, use high quality water, and have up to double the capacity of ordinary high frequency systems. Foliar cooling systems are sequenced so that the leaves are kept wet. Water is applied until the leaf surfaces are saturated, shut off until they are nearly dry, then reapplied. This generally requires having 1/4 to 1/6 of the system in operation simultaneously and cycling the system once every 15 to 40 min depending on system capacity, crop size, and climatic conditions. For example, a system for cooling trees might be operated 6 out of every 30 min so that 1/5 of the area is being sprinkled at any one time. Foliar cooling systems must have sufficient capacity to satisfy the evaporation demand on a minute-by-minute basis throughout the peak use hours during the peak use days. To accomplish this, the system capacity must be 1.5 to 2.5 times as great as is required for a conventional periodic-move system.

Such systems are capable of all the previously listed uses except providing *full* frost protection.

Frost Protection.—System capacity requirements for frost protection depend on lowest expected temperature, type of frost (radiant or advective), relative humidity, wind movement, crop height, and cycle time (or turning speed) of the sprinklers.

The basic process of overhead freeze control requires that a continuous supply of water be available at all times. The protective effect of sprinkling comes mainly from the 144 BTU of latent heat released per pound of water during the actual freezing of the water. In addition, a small amount of heat (one BTU per pound of water per degree Fahrenheit temperature drop) comes from the water as it cools to the freezing point. By using dew point temperature, humidity and temperature effects can be combined. As a general rule, with sprinklers turning faster than 1.0 rpm and winds up to 1 mph an application rate of 0.15 iph (65 gpm per acre) should provide overhead freeze protection down to a dew point temperature of 20°F. For every degree above or below a dew point temperature of 20°F the application rate can be decreased or increased by 0.01 iph (4.3 gpm per acre).

It is essential that frost protection systems be turned on before the dew point temperature drops below freezing and left operating until all the ice has melted the following morning. Where the dew point temperatures are apt to be low for long periods of time on consecutive days, the potential damage to trees from the ice load may be so great that overhead freeze control is impractical.

To protect against minor frosts having dew point temperatures of 28° or 29°F, use under-tree sprinkler systems with every other sprinkler operating and over-crop systems of limited capacity that can be rapidly sequenced. Such systems may use only 25 to 30 gpm per acre.

Bloom Delay.—Bloom delay is a means of cold protection wherein woody plants are cooled by sprinkling during the dormant season to delay budding until there is little probability of a damaging frost. Such systems are similar to crop cooling systems, but they are generally cycled so that half of the system is operating simultaneously. The system capacity to do this is governed by equipment and distribution uniformity considerations. An application rate of 0.10 to 0.12 iph is about as low as can be practically achieved with ordinary impact sprinklers. Operating half of such a system simultaneously requires 22 to 26 gpm per acre.

Continuous-Move Systems

Because center-pivot systems are completely automatic, it is relatively easy to carefully manage soil-moisture levels.

Ordinary Irrigation.—Center-pivot systems have the same attributes for ordinary irrigation as fixed systems. However, mechanical breakdown is more likely. Therefore, it is advisable to allow some reserve capacity (time) and use the same system capacity as for a conventional periodic-move system.

High Frequency.—Where high frequency irrigation is used for the same purposes described above, both fixed and center-pivot systems should have similar capacities. These comments also hold true where high frequency irrigation is used in arid areas to reduce runoff if the soil-crop system has a low water-holding capacity.

Limited Irrigation.—On crop-soil systems where there is 5.0 in or more water storage capacity, limited irrigation can be used during the peak-use period without appreciably affecting the yields of many crops. The use of light, frequent irrigation makes it practical to gradually deplete deep soil moisture during the peak use periods when the system capacity is inadequate to meet crop moisture withdrawal rates.

Light, frequent watering of the topsoil plus the gradual withdrawal of moisture from the subsoil can produce optimum crop yield when the system capacity is limited. But when subsoil moisture is inadequate, light, frequent irrigation resulting in heavy moisture losses from evaporation may be an inefficient use of a limited supply of water and may also increase salinity. Under these conditions, deeper less frequent irrigations may produce better yields.

System capacities as low as 60 percent of the recommended value for ordinary periodic-move systems may be adequate. But before determining the area that can be irrigated with a limited flow rate, a careful soil-moisture budget account should be constructed for the peak-use period.

Depth of Application

The calculated depth of application should be obtained for the crop-soil-water relationships at the proposed system location. Whenever possible, the depth should be based on local experience or on irri-

gation guides. In the absence of these, Chapter 1 can be used to gain an insight into the computation process.

Water-Holding Capacity

Soils of various textures have varying abilities to retain water. Except in the case of required periodic leaching, any irrigation beyond the field capacity of the soil is an economic loss. Table 11-1, which was taken from Chapter 1, gives typical ranges of available water-holding capacities of soils of different textures (field capacity minus permanent wilting point) and is presented here for convenience. If local data are not available, the listed averages may be used as a guide.

The total amount of soil water available for plant use in any soil is the sum of the available water-holding capacities of all horizons occupied by plant roots.

Table 11-1.—Range in available water-holding capacity of soils of different texture [1]

	Inches of water per foot of depth	
	Range	Average
1. Very coarse texture—very coarse sands	0.40 to 0.75	0.5
2. Coarse texture—coarse sands, fine sands, and loamy sands	0.75 to 1.25	1.0
3. Moderately coarse texture—sandy loams	1.25 to 1.75	1.5
4. Medium texture—very fine sandy loams, loams, and silt loams	1.50 to 2.30	2.0
5. Moderately fine texture—clay loams, silty clay loams, and sandy clay loams	1.75 to 2.50	2.2
6. Fine texture—sandy clays, silty clays, and clays	1.60 to 2.50	2.3
7. Peats and mucks	2.00 to 3.00	2.5

[1] Chapter 1, Section 15, *Soil-Plant-Water Relationships*.

Root Depth

Typical plant feeder root and total root depth are given in many references; however, the actual depths of rooting of the various crops are affected by soil conditions and should be checked at the site. Where local data are not available and there are no expected root restrictions, table 11-2 can be used as a guide to estimating the effective root depths of various crops.

The values given are averages selected from several references. They represent the depth at which crops will get most of their needed water when they are grown in a deep, well-drained soil that is adequately irrigated.

Application Depth and Frequency

For periodic-move, and low-frequency continuous-move systems such as traveling sprinklers, it is desirable to irrigate as infrequently as practical to reduce labor costs. A general rule of thumb for crops in arid and semiarid regions is that the soil moisture deficit (SMD) within the root zone should not fall below 50 percent of the total available-water-holding capacity. This is a management-allowed deficit, MAD = 50%. It is also desirable to bring the moisture level back to field capacity with each irrigation; therefore, the duration of each irrigation is identical.

In humid regions it is necessary to allow for rains during the irrigation period; however, the 50 percent limitation on soil moisture depletion should be followed for design purposes.

Local soil conditions, soil management, water management, and economic considerations determine the amount of water used in irrigating and the rate of water application. The standard design approach has been to determine the amount of water needed to fill the entire root zone to field capacity and, then, to apply at one application a larger amount to account for evaporation, leaching, and efficiency of application. The traditional approach to the frequency of application has been to assume MAD = 50%, then take the number of inches of water in the root zone reservoir that can be extracted and, using the daily consumptive use rate of the plant, determine how long this supply will last. Such an approach is useful only as a guide to irrigation requirements because many factors affect the amount of irrigation water and the timing of applications for optimal design and operation of a system.

Table 11-2. Effective crop root depths that would contain approximately 80 percent of the feeder roots in a deep, uniform, well-drained soil profile [1]

Crop	Root depth (ft)	Crop	Root depth (ft)
Alfalfa	4.0 to 6.0	Parsnip	2.0 to 3.0
Almonds	2.0 to 4.0	Passion fruit	1.0 to 1.5
Apple	2.5 to 4.0	Pastures (annual)	1.0 to 2.5
Apricot	2.0 to 4.5	Pastures (perennial)	1.0 to 2.5
Artichoke	2.0 to 3.0	Pea	1.5 to 2.0
Asparagus	6.0	Peach	2.0 to 4.0
Avocado	2.0 to 3.0	Pear	2.0 to 4.0
Banana	1.0 to 2.0	Pepper	2.0 to 3.0
Barley	3.0 to 3.5	Plum	2.5 to 4.0
Bean (dry)	1.5 to 2.0	Potato (Irish)	2.0 to 3.0
Bean (green)	1.5 to 2.0	Potato (sweet)	2.0 to 3.0
Beans (lima)	3.0 to 5.0	Pumpkin	3.0 to 4.0
Beet (sugar)	1.5 to 2.5	Radish	1.0
Beet (table)	1.0 to 1.5	Safflower	3.0 to 5.0
Berries	3.0 to 5.0	Sorghum (grain and sweet)	2.0 to 3.0
Broccoli	2.0	Sorghum (silage)	3.0 to 4.0
Brussel sprout	2.0	Soybean	2.0 to 2.5
Cabbage	2.0	Spinach	1.5 to 2.0
Cantaloup	2.0 to 4.0	Squash	2.0 to 3.0
Carrot	1.5 to 2.0	Strawberry	1.0 to 1.5
Cauliflower	2.0	Sugarcane	1.5 to 3.5
Celery	2.0	Sudangrass	3.0 to 4.0
Chard	2.0 to 3.0	Tobacco	2.0 to 4.0
Cherry	2.5 to 4.0	Tomato	2.0 to 4.0
Citrus	2.0 to 4.0	Turnip (white)	1.5 to 2.5
Coffee	3.0 to 5.0	Walnuts	5.5 to 8.0
Corn (grain and silage)	2.0 to 3.0	Watermelon	2.0 to 3.0
Corn (sweet)	1.5 to 2.0	Wheat	2.5 to 3.5
Cotton	2.0 to 6.0		
Cucumber	1.5 to 2.0		
Eggplant	2.5		
Fig	3.0		
Flax	2.0 to 3.0		
Grapes	1.5 to 3.0		
Lettuce	0.5 to 1.5		
Lucerne	4.0 to 6.0		
Oats	2.0 to 2.5		
Olives	2.0 to 4.0		
Onion	1.0		

[1] Soil and plant environmental factors often offset normal root development. Soil density, pore shapes and sizes, soil-water status, aeration, nutrition, texture and structure modification, soluble salts, and plant-root damage by organisms must all be taken into account.

Intake and Optimum Application Rates

The rate at which water should be applied depends on:

1. The time required for the soil to absorb the calculated depth of application without runoff for the given conditions of soil, slope, and cover. The depth of application divided by this required time is the maximum application rate.

2. The minimum application rate that will result in uniform distribution and satisfactory efficiency under prevalent climatic conditions or that is practical with the system selected.

3. The amount of time it takes for irrigation to achieve efficient use of available labor in coordination with other operations on the farm.

4. The application rate adjusted to the number of sprinklers operating in the best practical system layout.

Chapter 1 has a discussion of intake rates and the effects of slope, vegetation, and soil condition. The rate of application should be planned so it is no higher by the end of an irrigation than the capacity of the soil to absorb water. Ideally intake versus time of application information should be developed by applying water at the expected sprinkling intensity of the system selected on crops, soils, and slopes similar to the expected site conditions. This information can often be obtained by examining an existing system, but it is difficult to set up an experiment to observe it.

On bare soils drop impact causes surface sealing and reduces infiltration. The kinetic energy of a falling drop is the product of one-half its mass and the square of its velocity. Drop sizes range from 0.5 to 5.0 millimeters (mm) and have terminal falling velocities ranging from about 6 to 30 ft/s, respectively. With a typical fall distance equivalent to about 10 to 20 ft, most drops come close to reaching their respective terminal velocities. Table 11-3 presents terminal velocities and kinetic energies associated with different drop sizes.

Drop size is reduced as pressure increases (fig. 11-15), or as nozzle size decreases. Drop sizes can also be reduced by using means other than high pressures to cause jet breakup.

Table 11-3. Terminal velocities and kinetic energies associated with different size raindrops

Drop size (mm)	Volume (mm^3)	Terminal velocity (ft/s)	Kinetic energy values: in relation to a 1.0-mm drop	Kinetic energy values: per inch of rain, ft-lb/ft^2
0.5	0.066	5.92	0.0324	2.8
1.0	0.523	12.55	1.0	12.7
1.5	1.77	17.40	6.5	24.5
2.0	4.19	21.20	22.75	36.3
2.5	8.19	23.95	57.0	46.4
3.0	14.2	25.90	115.7	54.2
3.5	22.5	27.40	205.0	60.6
4.0	33.5	28.51	332.0	65.5
4.5	47.8	29.30	499.0	69.3
5.0	65.5	29.80	707.5	71.7

Some such devices are the use of pins penetrating the jet near the nozzle orifice; using sharp orifices instead of tapered nozzles; using triangular, rectangular, or oval orifices; and using impinging jets. Because of escalating energy costs the interest in obtaining small drops without high pressures has been accelerated.

The surface sealing and reduction in infiltration caused by drop impact depends on the soil texture and structure, amount and type of crop cover, and the application rate. Figure 11-16 shows the general relation between drop size and reduction in infiltration rate on three different bare soils with an application rate of approximately 0.5 iph. The reduction in infiltration rate on the freshly tilled, heavy-textured soil approached the maximum level about 20 min after the beginning of the application.

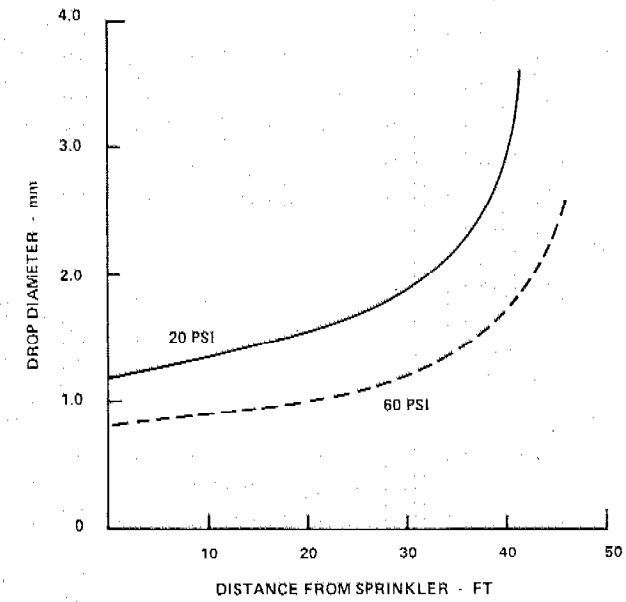


Figure 11-15.—Drop sizes at various distances from a standard 5/32-in nozzle operating at 20 and 60 psi.

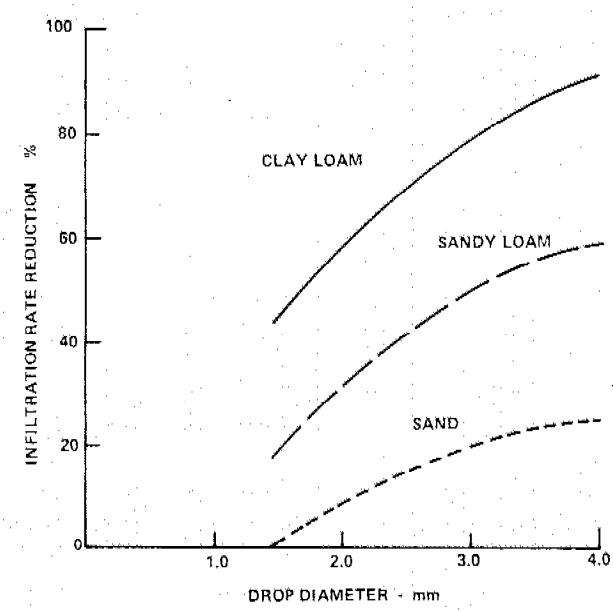


Figure 11-16.—Relation of infiltration rate reduction due to sprinkling three different soils at an application rate of approximately 0.5 iph.

Impact sprinklers produce a circular wetted area. At any one moment, all of the water in the jet lands in a small segment of the total wetted area. Usually the application rate on the area exceeds the infiltration capacity of the soil. The excess water momentarily ponds, forming a film on the soil surface that lubricates the surface soil particles and reduces to zero surface tension forces that might otherwise help hold the surface soil grains in place. Thus, droplets striking the wet surface tend to dislodge soil particles which then become suspended and settle out on the soil surface. These particles are carried into the soil by the infiltrating water, causing vertical erosion, surface sealing, and compaction.

The average application rate from a sprinkler is computed by:

$$I = \frac{96.3 \times q}{S_\ell \times S_m} \qquad (11\text{–}2)$$

where

I = average application rate (iph)
q = sprinkler discharge (gpm)
S_ℓ = spacing of sprinklers along the laterals (ft)
S_m = spacing of laterals along the mainline (ft)

Typically, an impact sprinkler with a 5/32-in nozzle operating at 50 psi and discharging 5 gpm would be spaced on a 30- by 50-ft spacing. From equation 2 the average application rate is 0.32 iph.

To compute the average instantaneous application rate (I_i) for a sprinkler having a radius of throw (R_j) and wetting an angular segment (S_a) equation 2 can be modified to:

$$I_i = \frac{96.3 \times q}{\pi (R_j)^2 \times S_a/360^\circ} \qquad (11\text{–}2a)$$

If the above sprinkler produced a wetted radius of R_j = 45 ft and the jet stream wetted an angular segment of $S_a = 6^\circ$, then I_i = 4.5 iph. This is considerably higher than the infiltration rate of most any agricultural soil except during the first moments of an irrigation.

Increasing sprinkler pressures or applying other means to reduce drop size also tends to decrease the instantaneous application rate. The smaller drops and lower I_i work together to reduce surface sealing. A jet of water rotating quickly over the soil surface will cause less sealing than a slower moving stream. The greatest drop impact and highest I_i is toward the periphery of throw and downwind from the sprinkler. A good rotational speed for the jet at the periphery of the wetted area is 5 ft/sec, which is a typical walking speed of 3.5 mph. Thus a typical impact sprinkler that produces a 90- to 100-ft wetted diameter should rotate about once a minute. However, a gun sprinkler that wets an area over 400 ft in diameter should turn only once every 4 to 5 min.

Periodic-Move and Fixed Systems

In all cases, the selected water-application rate must fall somewhere between the maximum and minimum values set forth at the beginning of the section.

The local irrigation guide gives suggested values for maximum water-application rates for different soils and for different slopes and cover. Maximum application rates for good ground cover should be used only when such cover can be established and maintained. Table 11–4 can be used for suggested maximum application rate values for periodic-move systems. The table is based on average soil conditions for the irrigation of all crops, except grasses and alfalfa, on various slopes. For bare ground and poor soil conditions the values should be reduced about 25 percent. For grasses and alfalfa the values may be increased about 25 percent. In addition, application rates should be reduced 25 percent for gun sprinklers, because they produce an abundance of large diameter drops and have high instantaneous application rates.

For most irrigated crops, the minimum practical rate of application to obtain reasonably good distribution and high efficiency under favorable climatic conditions is about 0.15 iph. If high temperatures and high wind velocities are common, the minimum application rate will be higher. The establishment of minimum application rates for local conditions requires experience and judgment.

Once maximum and minimum rates of application have been determined, the designer needs to arrive at a rate that requires a time of setting that fits into the farm operation schedule. For periodic-move systems, it is usually desirable to have intervals that give one, two, or at most three changes per day and that avoid nighttime changes. Changes just before or after mealtimes leave most of the day for other work. For fixed systems (especially automated ones) any number of changes per day can be made.

Table 11-4.—Suggested maximum application rates for sprinklers for average soil, slope, and tilth

Soil texture and profile	0-5% Slope (in/hr)	5-8% Slope (in/hr)	8-12% Slope (in/hr)	12-16% Slope (in/hr)
1. Coarse sandy soil to 6 ft	2.0	1.5	1.0	0.50
2. Coarse sandy soils over more compact soils	1.5	1.0	0.75	0.40
3. Light sandy loams to 6 ft	1.0	0.80	0.60	0.40
4. Light sandy loams over more compact soils	0.75	0.50	0.40	0.30
5. Silt loams to 6 ft	0.50	0.40	0.30	0.20
6. Silt loams over more compact soils	0.30	0.25	0.15	0.10
7. Heavy-textured clays or clay loams	0.15	0.10	0.08	0.06

Continuous-Move Systems

Traveling sprinklers, like periodic-move systems, are usually managed to apply relatively deep irrigations. Furthermore, drop sizes tend to be large so values from Table 11-4 should be reduced by 25 percent for use as guides to selecting maximum application rates for traveling sprinklers.

It is practical to apply frequent, light applications with center-pivot and linear-move systems. With light applications, up to 0.5 in of the applied water can be stored in small depressions on the soil surface. Because of this, the peak application rates near the end of center-pivot or linear-move laterals operating on a 1- or 2-day cycle can often be more than 100 percent greater than specified in Table 11-4 and not cause runoff on slopes of less than 8 percent. This is fortunate because it is difficult to nozzle center-pivot systems that have a maximum application rate of much less than 1.0 iph.

Sprinkle Irrigation Efficiency

Irrigation efficiency is a concept that is used extensively in system design and management. It can be divided into two components, uniformity of application and losses. If either uniformity is poor or losses are large, efficiency will be low. Several factors affect the water-application efficiency of sprinkle irrigation systems:

1. Variation of individual sprinkler discharge along lateral lines can be held to a minimum by proper lateral design.
2. Variation in moisture distribution within the sprinkler-spacing area is caused primarily by wind movement. For periodic move, fixed, and traveling sprinklers this can be partially overcome by closely spacing sprinklers or tow paths to meet adverse wind conditions. In addition to the variation caused by wind, there is always a variability in the distribution pattern of individual sprinklers. The extent of this variability depends on sprinkler design, operating pressure, and sprinkler rotation. For center-pivot and linear-move systems wind distortion is not a serious problem because the sprinklers are spaced close together along the lateral, and the lateral is continuously moving.
3. Loss of water by direct evaporation from the spray increases as temperature and wind velocities increase and as drop size and application rate decrease.
4. Evaporation from the soil surface before the water reaches the plants decreases proportionally as greater depths of water are applied.

Uniformity

Distribution uniformity (DU) is a useful term for placing a numerical value on the uniformity of application. The DU indicates the uniformity of infiltration throughout the field.

$$DU = \frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} \times 100 \qquad (11\text{-}3)$$

The average low-quarter depth of water received is the average of the lowest one-quarter of the measured values where each value represents an equal area.

Another parameter that is used continuously to evaluate sprinkle irrigation uniformity is the uniformity coefficient developed by Christiansen[1]:

$$CU = 100\,(1.0 - \frac{\Sigma X}{mn}) \qquad (11\text{-}4)$$

where

X = absolute deviation of the individual observations from the mean (in)

[1] *Christiansen, J. E. 1942. Irrigation by sprinkling. University of California. Bull. No. 670.*

m = mean depth of observations (in)
n = number of observations

The test data for CU > 70% usually form a typical bell-shaped normal distribution and are reasonably symmetrical around the mean. Therefore CU can be approximated by:

$$CU \cong \frac{\text{Average low-half depth of water received}}{m} \times 100 \qquad \textbf{(11-4a)}$$

and the relationship between DU and CU can be approximated by:

$$CU = 100 - 0.63\,(100 - DU) \qquad \textbf{(11-5a)}$$

or

$$DU = 100 - 1.59\,(100 - CU) \qquad \textbf{(11-5b)}$$

Some of the things that affect uniformity tend to average out during a series of irrigation applications. Other aspects of nonuniformity tend to concentrate, that is, the same areas tend to be over- or under-irrigated during each irrigation application. Obviously, the major concern is with those aspects that concentrate in the problem areas.

Components of nonuniformity in sprinkle irrigation systems that tend to smooth out are:

1. Uneven operation of the sprinklers. This includes variations in turning speed regularity, variations in discharge between sprinklers caused by differences in nozzle size and wear, and irregularity of trajectory angle caused by riser straightness.

2. Uneven travel speed for moving sprinklers or time of set for stop-start systems. When the lack of uniformity in moving systems is caused by steep slopes or the weight of hose being dragged, there will be little tendency for this unevenness to smooth out. On the other hand, the lateral line set time for stop-start systems will generally smooth out randomly, especially if care is taken to alternate between day and night sets.

The following tend to concentrate unevenness:

1. Differences in sprinkler discharges throughout the system caused by elevation and friction loss.

2. Surface movement of water (both micro- and macro-runoff). Normally one thinks of all the water infiltrating into the soil where it falls. This is not always the case. For example, along the outer edges of center-pivot-irrigated fields the application rate is often about 1 iph, which is excessive for many soils.

3. Poor water distribution around field boundaries. This is especially true for giant sprinklers that by necessity have a poor watering pattern around all boundaries, and for center-pivots where an effort is made to irrigate a substantial distance past the end of the hardware. For example, the last 100 ft past the end of a 1,320 ft center-pivot lateral constitutes more than 13 percent of the area wetted of the system. The outer 100 ft of a 160-acre field irrigated with a giant sprinkler constitutes 15 percent of the field area. Tipping the risers inward along the outer lateral sets and using part-circle sprinklers on lateral ends where medium and small sprinklers are used can greatly improve the uniformity along the field edges.

Uneven aerial distribution of water has both a tendency to smooth out and a tendency to concentrate, resulting from overlap, sprinkler pattern shape, and wind effects on the overlap and pattern shape. Because the wind is usually different during each irrigation, there is some tendency for uniformity to improve over several irrigations. Also, alternating day and night sets and changing the lateral positions for each irrigation smooth out some unevenness. In general, close sprinkle spacings give higher uniformities irrespective of wind conditions. Continuously moving a sprinkler is similar to having an infinitely close sprinkler spacing along the direction of travel. Thus, continuous-move systems have potential for quite high uniformities regardless of winds, if the sprinkler spacing at right angles to the direction of movement is sufficiently close.

Most of the effort to evaluate sprinkle irrigation system uniformity and efficiency is done with can tests. Such tests typically measure only the uniformity problems associated with aerial distribution. With close sprinkler spacings on fixed systems and along moving laterals, a high level of uniformity with DU values above 90 percent is practical in the test area. However, the other problems causing lower uniformity reduce the highest practical overall DU to about 85 percent. A low DU or CU value indicates that losses due to deep percolation will be excessive if adequate irrigation is applied to all areas. Although the concept of low values is relative, values of DU < 72% (CU < 83%) are generally considered as being low even for general field and forage crops. For higher value crops DU > 80% (CU > 88%) are recommended.

The sprinkler's physical characteristics as well as nozzle size and pressure affect its performance. Therefore, the DU or CU values used for final de-

sign computations should be based on field or test facility data. Field evaluation techniques for estimating the uniformity of periodic-move, traveling, and center-pivot sprinklers are presented in the following sections. However, when test data are not available in general planning for the most common periodic-move sprinkler spacings, tables 11-5 through 11-8 can be used to obtain estimated values of CU for various wind conditions and application rates.

The average uniformity of the catch data of two irrigations is always higher than the average uniformities of the two irrigations measured individually, because of changes in wind and water jets. Uniformity can be further improved by positioning the laterals midway between the previous settings for alternate irrigations. This practice is called alternate sets, and it halves the lateral spacing for the pair of irrigations. The uniformity of a pair of irrigations using alternate sets can be approximated by:

$$CU_a = 10\sqrt{CU} \qquad \textbf{(11-6a)}$$

or

$$DU_a = 10\sqrt{DU} \qquad \textbf{(11-6b)}$$

For gun or boom sprinklers CU values of 60 to 75 percent are typical for low and moderate wind conditions. These sprinklers are not recommended for use in high winds. By using alternate sets along the lateral or between laterals when practical, CU_a values of about 80 percent can be obtained in the central portion of a field.

For traveling sprinklers the effective spacing along the tow path that corresponds to the lateral is zero. Thus, the expected CU in the central portion of the field and in low to moderate winds should be similar or slightly better than the CU_a of 80 percent for periodic-move gun or boom sprinklers.

Center-pivot and linear-move systems produce high uniformities because the sprinklers are usually relatively close together on the moving laterals. With proper nozzling CU > 94%, DU > 90% can be expected in the area under the system hardware in relatively level fields. The same high uniformities can be maintained even on steep, undulating fields if flow control nozzle sprinklers or other means of countering elevation effects by regulating pressure, flow, or system speed are used. When large end gun sprinklers are used on center-pivots, the average CU of the whole irrigated area drops about 1 percent for each 1 percent of area covered past the end of the hardware.

Water Loss

Although efforts are often concentrated on evaluating systems by dealing with uniformity problems, loss of water also reduces system efficiency. Frequently, designers assume that systems will be perfectly managed and losses will almost be eliminated, but this is seldom the case. Overwatering is perhaps the greatest cause of loss in any irrigation system. Other major causes of losses associated with sprinkle irrigation are:

1. Direct evaporation from droplets and from wet soil surfaces and transpiration from unwanted vegetation.
2. Wind drift.
3. Leaks and system drainage.

Wind drift and evaporation losses may be less than 5 percent when irrigating a crop with a full vegetative canopy in low winds. More commonly, wind drift and evaporation losses range between 5 and 10 percent. However, under very severe conditions they can be considerably greater. Figure 11-17 has been developed as a guide for estimating the effective portion of the water applied that reaches the soil-plant surface (R_e). The values given for effectiveness for different potential evapotranspiration rates are based on an assumed full plant canopy and 24-hr applications. The fine-spray curves are based on 3/16-in nozzles operating at 60 psi in a 40- x 60-ft spacing. The coarse spray is for 3/16-in nozzles operating at 30 psi in a 30- x 60-ft spacing.

To use figure 11-17, it is necessary to know whether the spray from a sprinkler is coarse, fine, or somewhere in between. To make this determination a coarseness index (CI) is used. This index can be calculated by the following method:

$$CI = \frac{P^{1.3}}{B} \qquad \textbf{(11-7)}$$

where

P = Nozzle operating pressure (psi)
B = Nozzle size (64ths of an inch)

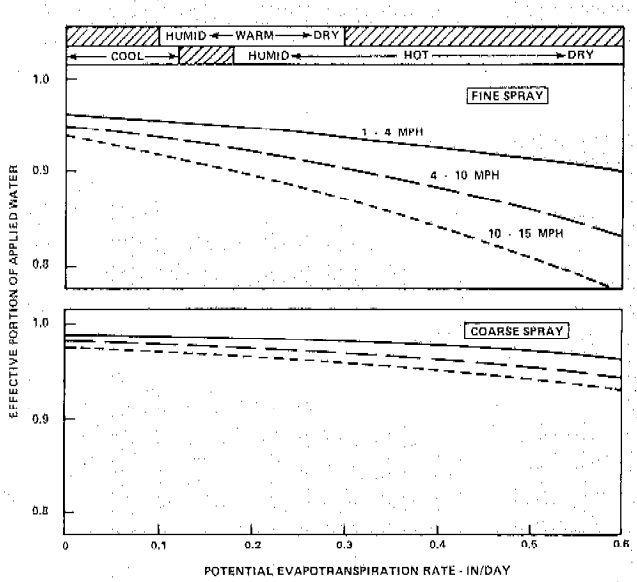


Figure 11-17.—Effective portion of water applied, R_e, by sprinkling with fine and coarse sprays in different wind conditions and with different potential evapotranspiration rates on crops with full canopies.

If the value of CI $\leq$ 7 the spray is coarse, and the lower portion of figure 11-17 should be used to find R_e. If CI $\geq$ 17 then the spray is fine, and the upper portion of the figure should be used. When the value of CI falls between 7 and 17 the R_e value may be interpolated by the formula:

$$R_e = \frac{(CI-7)}{10}(R_e)_c + \frac{(17-CI)}{10}(R_e)_f \qquad (11\text{-}8)$$

where R_e = Effective portion of applied water
$(R_e)_c$ = R_e value found if the coarse spray curves are used
$(R_e)_f$ = R_e value found if the fine spray curves are used

For well-maintained systems, leaks and drainage losses can be held to less than 1 percent of system capacity or even eliminated by using antidrain valves at the sprinklers. However, poorly maintained systems have been known to have leakage and drainage losses of up to 10 percent.

Inherent to scheduling is the evaluation of the system to determine its efficiency and to locate potential areas for upgrading system performance. With scheduling and careful management the following improvements in irrigation efficiency appear reasonable.

1. Increases of 20 to 40 percent or more are feasible when irrigation water is plentiful, when there is supplemental rain, and when soils have low water-holding capacities.
2. Increases of 5 to 15 percent are often possible for high water-holding capacity soils and of 10 to 25 percent for low water-holding capacity soils when maximum production per unit of land is desired in arid zones with abundant water supplies.
3. In arid zones where water supplies are scarce and maximum productivity per unit of water used is desired, fields are often underirrigated. In such instances scheduling can at most increase efficiencies by 10 percent. Scheduling may be very useful, however, in determining the best time to apply the limited water available. This can be done by watering at the most strategic crop phenological development stage that results in maximum profit. By carefully analyzing and selecting the crops and planting dates, water requirements can be further reduced.

Application

Perhaps the most often used irrigation efficiency term is application efficiency (E_a). This is the ratio of the average depth of irrigation water stored in the root zone to the average depth of irrigation water applied.

The E_a only indicates the losses, since it merely shows the fraction of applied water stored within the root zone that is potentially accessible for evaporation and transpiration. Thus, E_a does not indicate the adequacy of the irrigation and, with exaggerated underirrigation, it can equal 100 percent.

To be more useful, an irrigation efficiency concept should combine some measure of uniformity, of adequacy of irrigation, and of losses. Such a concept is application efficiency of the low quarter (E_q). The E_q is a useful term for placing a numerical value on irrigation efficiency for *medium to high value crops*. For design purposes the ratio of the average low-quarter depth of irrigation water available to the plant to the average depth of irrigation water applied can be estimated by:

$$E_q = DU \times R_e \qquad (11\text{-}9)$$

where

E_q = Application efficiency of the low quarter (%)

DU = Distribution uniformity (%)
R_e = Effective portion of applied water from figure 11-17.

When the soil moisture deficit (SMD) is divided by E_q to determine the gross depth of irrigation, d, only about 10 percent of the area will remain below field capacity. Conversely, about 90 percent of the area will be adequately irrigated and will receive varying amounts of overirrigation. While this is practical for medium- to high-value crops, it is extravagant for low-value field and forage crops. For such crops an application efficiency based on the average low-half depth is more appropriate.

For design purposes, the application efficiency of the low half (E_h) can be estimated by:

$$E_h = CU \times R_e \qquad (11\text{-}10)$$

When E_h is used to estimate d, needed to replace a given SMD, only about 20 percent of the area will remain below field capacity.

The range of probable E_q and E_h values for the various types of sprinkle systems are:

Type	E_q	E_h
Periodic move lateral	60 to 75%	70 to 85%
Gun or boom sprinklers	50 to 60%	60 to 75%
Fixed lateral	60 to 85%	70 to 88%
Traveling sprinklers	55 to 67%	65 to 77%
Center-pivot	75 to 85%	80 to 88%
Lateral-move	80 to 87%	85 to 90%

The above efficiency values are based on full canopy crops and the assumption that the systems are well designed and carefully maintained. The values should be considered only estimates. Obviously, considerably lower values would be obtained with poor management or where systems are poorly designed or ill-suited to the prevailing conditions.

Design Procedure

The first step in the design procedure is to collect basic farm resource data. This information includes a topographic map showing obstacles and farm and field boundaries, as well as data on water resource quality and quantity, weather, crops, and soils. The farmer should be consulted about financial, labor, and management capabilities. Once the data on the farm's resources have been assembled, the system selection, layout, and hydraulic design process can proceed.

The four major components in a sprinkle system are shown in figure 11-18. The design process should begin with the sprinkler selection then continue with the system layout, followed by the design of the lateral, mainline, and pumping plant. To make a rational system selection, it may be necessary to design and analyze two or more systems and the farmer should carefully study the system ultimately selected.

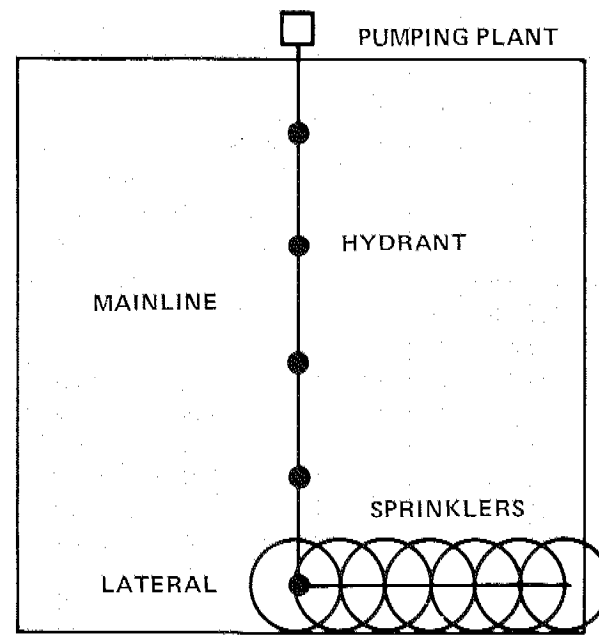


Figure 11-18.—Basic sprinkle system components.

Periodic-Move and Fixed Systems

The basic strategy for designing all periodic-move and fixed systems is the same as for hand-move systems. Much of the design described in this section also applies to continuous-move systems. For example, the design of mainlines and pumping

plants is similar for all systems. There are also many similarities between the sprinkler-head characteristics of periodic-move and those of continuous-move systems. Because of this overlap the sections on the continuous-move sprinklers will only contain material that is unique to those systems.

Sprinklers are classified according to their operating pressure range and their position in relation to irrigated crops. The different classifications, with the characteristics and adaptability of each, are given in table 11-5.

Sprinkler Selection

Actual sprinkler head selection is based on the discharge rate, height of trajectory, and sprinkler distribution characteristics desired. Sprinklers for periodic-move differ little from those for fixed-sprinkler systems. The main difference is that in fixed systems pipe lengths that are not even multiples of 10 ft are practical, and low discharge sprinklers set at wide spacings are chosen for economic reasons.

By keeping sprinkler discharge rates as low as possible while still using wide sprinkler spacings, the size and amount of pipe as well as labor are kept to a minimum. The sprinkler giving the most economical overall system should be selected if soil surface sealing and infiltration are not limiting factors. Quite often, however, when bare soil surfaces must be sprinkled, sprinklers having nozzles between 5/64 and 9/64 in and operating at pressures over 50 psi must be used.

Under-tree systems may require low trajectory sprinklers to reduce foliar wetting and interference. Under-tree sprinkling is required when the irrigation water is of such low quality that it will cause leaf burn. Variations in sprinkler design imposed by tree spacings and tree shapes are not detailed here. In general, however, sprinklers that produce an E-type pattern by throwing a greater volume of water to the outer perimeter of the wetting pattern produce the best under-tree results because tree interference tends to cause excess water application close to the sprinklers.

On over-crop systems in very windy areas, low-angle sprinklers with a trajectory of 18° to 21° produce better results than high-angle sprinklers with 25° to 28° trajectories. Many sprinkler manufacturers have compromised on a trajectory angle of between 22° and 24° to achieve reasonable performance under varying wind conditions. Where winds are always very low, high-angle sprinklers give the best results with a minimum of pressure.

Once the type of sprinkler has been determined, based on pressure limitations, application rates, cover conditions, crop requirements, and availability of labor, the next step is to determine the combination of sprinkler spacing, operating pressure, and nozzle sizes that will most nearly provide the optimum water-application rate with the greatest uniformity of distribution.

Distribution Uniformity.—The degree of uniformity obtainable depends primarily on the moisture-distribution pattern of the sprinkler and on the spacing of the sprinklers. Figure 11-19 shows the distribution pattern and precipitation profiles obtained from a typical double-nozzle sprinkler operating at proper pressure with no wind.

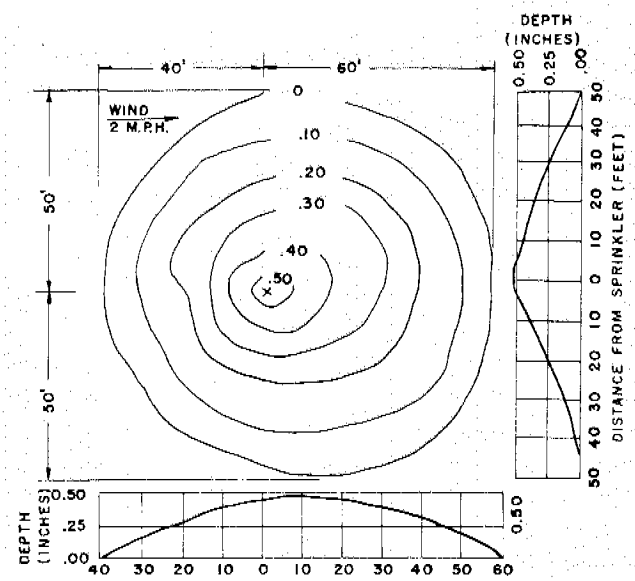


Figure 11-19.—Distribution pattern and precipitation profiles from a typical double-nozzle sprinkler operating under favorable conditions.

Each type of sprinkler has certain precipitation profile characteristics that change as nozzle size and operating pressure change. Each has an optimal range of operating pressures for each nozzle size. All manufacturers of revolving sprinklers recommend operating pressures or ranges of pressures that will result in the most desirable application pattern for each type of sprinkler and nozzle size. In selecting nozzle sizes and operating pressures for a required sprinkler discharge, the different pressures affect the profile as follows:

Table 11-5.—Classification of sprinklers and their adaptability

Type of sprinkler	Low pressure 5-15 psi	Moderate pressure 15-30 psi	Intermediate pressure 30-60 psi	High pressure 50-100 psi	Hydraulic or giant 80-120 psi	Under-tree long-angle 10-50 psi	Perforated pipe 4-20 psi
General characteristics	Special thrust springs or reaction-type arms.	Usually, single-nozzle oscillating or long-arm dual-nozzle design.	Either single or dual nozzle design.	Either single or dual-nozzle design.	One large nozzle with smaller supplemental nozzles to fill in pattern gaps. Small nozzle rotates the sprinkler.	Design to keep stream trajectories below fruit and foliage by lowering the nozzle angle.	Portable irrigation pipe with lines of small perforations in upper third of pipe perimeter.
Recommended minimum application rate	0.40 inch per hour.	0.20 inch per hour.	0.25 inch per hour.	0.50 inch per hour.	0.65 inch per hour.	0.33 inch per hour.	0.50 inch per hour.
Jet characteristics (assuming proper pressure-nozzle size relations)	Waterdrops are large due to low pressure.	Waterdrops are fairly well broken.	Waterdrops are well broken over entire wetted diameter.	Waterdrops are well broken over entire wetted diameter.	Waterdrops are extremely well broken.	Waterdrops are fairly well broken.	Waterdrops are large due to low pressure.
Moisture distribution pattern (assuming proper spacing and pressure-nozzle size relations)	Fair.	Fair to good at upper limits of pressure range.	Very good.	Good *except* where wind velocities exceed 4 miles per hour.	Acceptable in calm air. Severely distorted by wind.	Fairly good. Diamond pattern recommended where laterals are spaced more than one tree interspace.	Good rectangular pattern.
Adaptations and limitations.	Small acreages. Confined to soils with intake rates exceeding 0.50 inch per hour and to good ground cover on medium- to coarse-textured soils.	Primarily for under-tree sprinkling in orchards. Can be used for field crops and vegetables.	For all field crops and most irrigable soils. Well adapted to over-tree sprinkling in orchards and groves and to tobacco shades.	Same as for intermediate pressure sprinklers except where wind is excessive.	Adaptable to close-growing crops that provide a good ground cover. For rapid coverage and for odd-shaped areas. Limited to soils with high intake rates.	For all orchards or citrus groves. In orchards where wind will distort over-tree sprinkler patterns. In orchards where available pressure is not sufficient for operation of over-tree sprinklers.	For low-growing crops only. Unsuitable for tall crops. Limited to soils with relatively high intake rates. Best adapted to small acreages of high-value crops. Low operating pressure permits use of gravity or municipal supply.

1. At the lower side of the specified pressure range for any nozzle, the water remains in large drops. When pressure falls too low, the water from the nozzle falls in a ring a distance away from the sprinkler, giving a poor precipitation profile (fig. 11-20A).

2. Within the desirable range, the sprinkler should produce the precipitation profile shown in figure 11-20B.

3. On the high side of the pressure range, the water from the nozzle breaks up into fine drops and settles around the sprinkler (fig. 11-20C). Under such conditions the profile is easily distorted by wind.

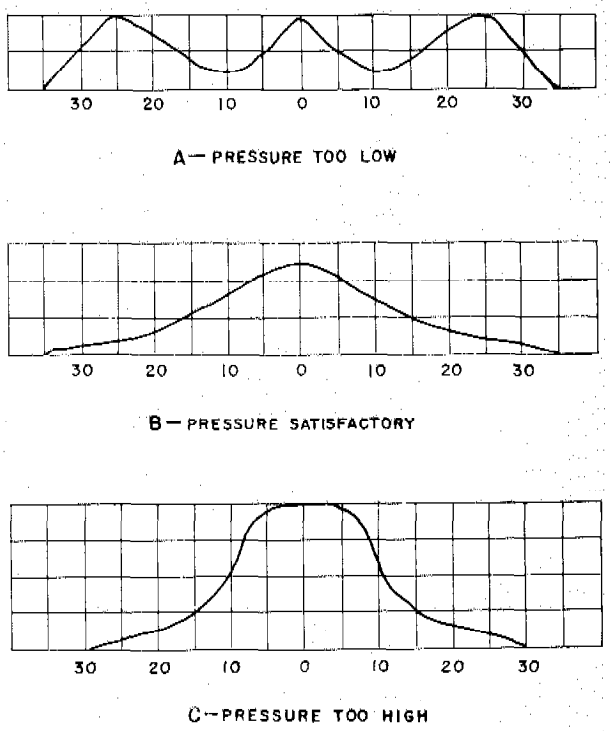


Figure 11-20.—Effect of different pressures on precipitation profiles for a typical double-nozzle sprinkler.

Wind distorts the application pattern, and the higher the wind velocity, the greater the distortion. Figure 11-21 shows test results of an intermediate double-nozzle sprinkler operating under a wind velocity of 10.7 mph. This distortion must be considered when selecting the sprinkler spacing.

The depth of water applied to an area surrounding a revolving sprinkler varies with the distance from the sprinkler. Thus, to obtain a reasonably high uniformity of application, water from adjacent sprinklers must be added. Figure 11-22 illustrates the depth of distribution obtained by overlapping.

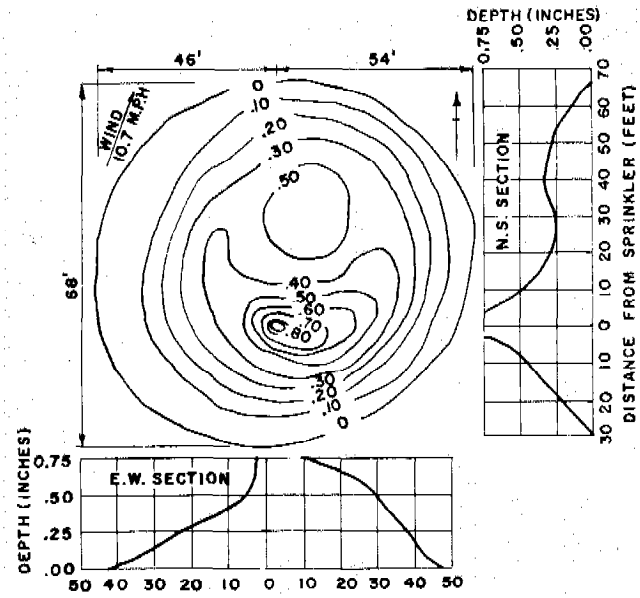


Figure 11-21.—Effect of wind on distribution pattern and precipitation profiles from a typical intermediate double-nozzle sprinkler.

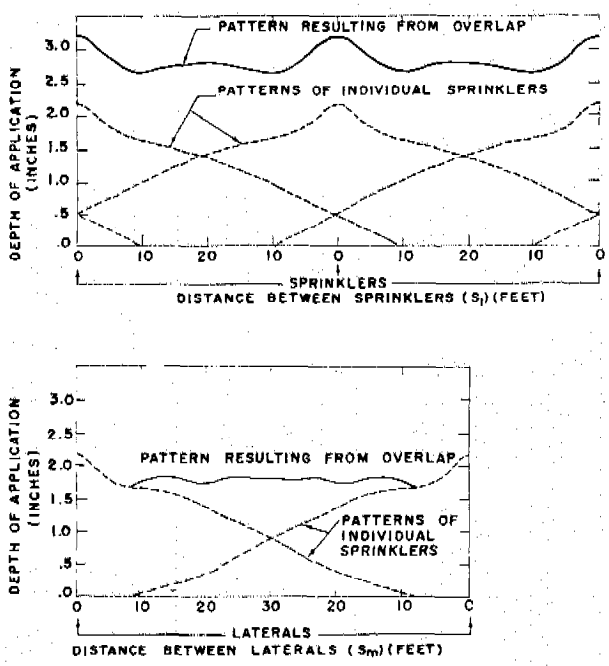


Figure 11-22.—Example of the distribution patterns between sprinklers along the lateral and between laterals.

Manufacturers of sprinklers specify a wetted diameter for all nozzle sizes and operating pressure combinations for each type of sprinkler in their line. Since sprinkler-spacing recommendations commonly are made on the basis of these diameters, the planner must carefully consider them. The precipitation profile is also important when making sprinkler-spacing recommendations. Different sprinkler nozzling, pressure, and physical characteristics produce different precipitation profiles. Figure 11-23 shows a stylized set of potential sprinkler profiles and optimum spacings.

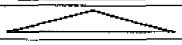
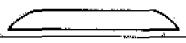
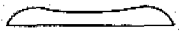
SPRINKLER PROFILE		RECOMMENDED SPACING AS A PERCENTAGE OF DIAMETER		
TYPE	SHAPE	SQUARE	TRIANGULAR EQUILATERAL	RECTANGULAR SHORT x LONG
A		50	50	40 x 60 to 65
B		55	66	40 x 60
C		60	65	40 x 60 to 65
D		40 70 (FAIR)	70 to 75	40 x 70 to 75
E		40 80 (FAIR)	80	40 x 80

Figure 11-23. Christiansen's geometrical sprinkler profiles and optimum spacings as a percentage of the effective wetted diameter.

Certain sprinklers under specific conditions produce a typical precipitation profile as shown in figure 11-23. Each profile type has its spacing recommendations based on the diameter of effective coverage under the particular field conditions of operation. Conditions that affect both the diameter and profile characteristics are direction and velocity of the wind measured from the ground level to the top of the jet trajectory, angle of stream trajectories, height and angle of risers, turbulence in the stream of water entering and leaving the nozzle, pressure at the nozzle, size of the nozzle, speed and uniformity of rotation and characteristics of the driving mechanism such as the shape, angle, and frequency of the spoon and lever action. With such a complex set of conditions the practical way of determining the profile type and diameter is by placing catchment gages in the precipitation area and evaluating the results.

Profile types A, B, and C (fig 11-23) are characteristic of sprinklers having two or more nozzles. Profile types C and D are characteristic of single-nozzle sprinklers at the recommended pressures.

Profile type E is generally produced with gun sprinklers or sprinklers whose pressure at the nozzle or nozzles is lower than those recommended for the nozzle sizes concerned. Sprinklers with straightening vanes just upstream from the range nozzle also tend to produce an E type profile. The vanes increase the diameter of throw, but pressures must be increased by 10 to 15 psi to keep the dip in the center of the profile from becoming too low.

The spacing recommendations in figure 11-23 should give acceptable application uniformities when a realistic effective diameter is used. Operating conditions in the field affect both the diameter and the precipitation profile. Wind is the chief modifier reducing the diameter of throw and changing profiles to a mixed type such as a short A or B type on the upwind side of the sprinkler, a D or E type downwind, and a C type cross wind (fig. 11-21). The diameter of throw of a sprinkler as listed in the manufacturer's brochure is often for no wind and to the farthest droplet from the sprinkler. Under field operating conditions with 0-3 mph wind, such diameters should be shortened by 10 percent from the listed figure to obtain the effective diameter. Effective diameters should be further reduced for winds exceeding 3 mph. A reduction of 2.5 percent for each mph over 3 pmh is a fair estimate for the usual range of wind conditions under which sprinklers are operated.

Generally, highest uniformities are obtained at spacings of 40 percent or less of the diameter, but such close spacings raise both precipitation rates and costs. Overly conservative or optimistic spacings between lines can result in poor uniformities of coverage. Certain profile types, notably D and E, have a narrow range at high uniformity for extended spacing between lines. Thus the uniformity can change drastically with changes in wind speed. Unfortunately, with D and E profiles the uniformity can actually decrease as wind velocity decreases because of too much overlap.

Under field operating conditions, a variety of wind speeds and directions usually exist during the irrigation set. Therefore, a mixture of profiles is produced. As a general recommendation, moderate- and intermediate-pressured sprinklers should be spaced as follows:

1. Rectangular spacing of 40 by 67 percent of the effective diameter based on the average wind speed during the setting.
2. Square spacing of 50 percent of the effective

diameter based on average wind speed during the setting.

3. Equilateral triangular spacing of 62 percent of the effective diameter based on average wind speed during the setting.

Application Uniformity.—Obviously the spacing of sprinklers along the lateral (S_l) and along the main (S_m) affects the amount of overlap and, consequently, the uniformity and depth of application. Figure 11-24 shows the data from a typical field test. (The procedure for collecting the data is presented at the end of this section.) The basic catch data that were measured in milliliters have been converted to the application rates in inches per hour received at each location. Obviously, these rates are equivalent to depths when computing DU and CU values.

Figure 11-25 shows the data gathered between sprinklers 5 and 6 from figure 11-24 overlapped to simulate a 50-ft lateral spacing, $S_m = 50$ ft. The sprinklers were spaced 30 ft apart on the lateral, $S_l = 30$ ft; thus, the sprinkler spacing is referred to as a 30- by 50-ft spacing. The right side catch is added to the left side catch: the totals at each point represent a complete 1-hour irrigation for a 30- by 50-ft spacing. For the simulated 50-ft lateral spacing, the total catch at all 15 grid points is 3.97, which gives:

$$\text{Average catch rate} = \frac{3.97}{15} = 0.265 \text{ iph}$$

The average of the lowest one-quarter of the catch rates (use 4 out of 15) is:

$$\text{Average low quarter rate} =$$

$$\frac{0.20 + 0.22 + 0.22 + 0.23}{4} = 0.218 \text{ iph}$$

and from equation 3:

$$DU = \frac{0.218}{0.265} \times 100 = 82\%$$

To estimate the CU, from the mean one must determine the total deviations (X) by summing the deviations of the individual observations as shown by the numbers in parentheses on figure 11-25. The sum of these deviations is 0.51 and from equation 4:

$$CU = 100\left(1.0 - \frac{0.51}{0.26 \times 15}\right) = 87\%$$

As mentioned earlier, the CU can be approximated from the average low-half and mean values of the observations by equation 4a:

$$CU \cong \frac{1.6/7}{0.26} \times 100 = 88\%$$

Or, the CU can be approximated from the DU = 82% by equation 5a:

$$CU \cong 100 - 0.63\,(100 - 82) = 89\%$$

The deviations between the approximated values of CU and the value computed by equation 4 result from the small size of the sample and consequent deviation from a typical bell-shaped normal distribution.

Although the system was designed for a 50-ft lateral move, the effect on uniformity of the other move distances can also be evaluated from the field test data. Table 11-6 is a summary of computations for DU and CU for four typical lateral spacings, for the area between sprinklers 5 and 6 and the area between the sprinklers 4 and 5, computed as above from the data in figure 11-24 parts 8 and 10. Comparison of percentage values illustrates the problem of choosing a representative or minimum site. Some other sites in the field undoubtedly were poorer and some were better than the tested site; therefore, computed uniformities are not universally applicable, but they are useful for evaluating the system. Even with nearly identical sprinklers operating simultaneously, the uniformity test values may vary by a significant percentage. Usually the accuracy of the catch data itself results in a deviation

Table 11-6.—DU and CU values of four standard sprinkler spacings for areas between sprinklers 5 and 6 and sprinklers 4 and 5 (fig. 11-24)

Test area criteria	Sprinkler spacing (feet)			
	30 × 40	30 × 50	30 × 60	30 × 60 alt[1]
	Area between sprinklers 5 and 6			
DU	81	84	64	91
CU	87	87	75	93
	Area between sprinklers 4 and 5			
DU	79	76	50	82
CU	86	89	70	91

[1] The alternate set values are the same as for a 30 × 30-ft spacing.

1. Location *Field C-22*, observer *JLM*, date *9-30-75*
2. Crop *Tomatoes*, root zone depth *4.0* ft, MAD *50%*, MAD *4.4* in
3. Soil: texture *clay loam*, available moisture *2.2* in/ft, SMD *4.4* in
4. Sprinkler: make *Rain Bird*, model *29B*, nozzles *5/32* by ____ in
5. Sprinkler spacing *30* by *50 ft*, irrigation duration *23.5* hr
6. Rated sprinkler discharge *4.4* gpm at *40* psi giving *0.28* in/hr
7. Lateral: diameter *2* in, slope *1½%*, riser height *18* in
8. Actual sprinkler pressure and discharge rate:

	Sprinkler location number on test lateral					
	1	*4*	*5*	*6*	*10*	*15 end*
Initial pressure (psi)	*45*	*40*	*40*	*40*	*39*	*40*
Final pressure (psi)	*45*		*40*		*39*	*40*
Catch volume (gal)	*1.0*	*1.0*	*1.0*	*1.0*		*1.0*
Catch time (min or sec)	*0.21*	*0.22*	*0.22*	*0.22*		*0.22*
Discharge (gpm)	*4.8*	*4.6*	*4.6*	*4.6*		*4.6*

9. Wind: Direction relative to

Part 10: initial ↘, during ↙, final ↙
Speed (mph): initial *2±*, during *5±*, final *5±*

10. Container grid test data in units of *ml*, volume/depth *200* ml/in

Container grid spacing *10* by *10* ft

Test: start *2.55 pm*, stop *4:30 pm*, duration *1* hr *35* min = *1.58* hr

___	___	___	*32* / *.10*	*68* / *.21*	*77* / *.24*	*90* / *.28*	*73* / *.23*	*66* / *.21*	*9* / *.03*	___	*ml* / *iph*	___
___	___	___	*35* / *.11*	*66* / *.21*	*84* / *.26*	*100* / *.31*	*100* / *.31*	*52* / *.16*	*3* / *.01*	___	___	___
___	___	___	*32* / *.10*	*50* / *.16*	*70* / *.22*	*104* / *.32*	*99* / *.31*	*48* / *.15*	*12* / *.04*	___	___	___
___	___	___	*31* / *.10*	*74* / *.23*	*88* / *.27*	*104* / *.32*	*86* / *.27*	*56* / *.17*	*11* / *.03*	___	___	___
___	___	___	*27* / *.08*	*64* / *.20*	*80* / *.25*	*96* / *.30*	*112* / *.35*	*62* / *.19*	*9* / *.03*	___	___	___
___	___	___	*20* / *.06*	*49* / *.16*	*59* / *.19*	*107* / *.33*	*87* / *.27*	*36* / *.11*	*13* / *.04*	___	___	___

11. Evaporation container: initial *2.15* final *2.10* loss *0.05* in
12. Sprinkler pressures: max *45* psi; min *39* psi, ave *40* psi
13. Comments: *Test duration was too short. Depths caught measured in 1000-ml graduated cylinder. Wind velocities are less than normal.*

Figure 11-24—Sprinkler-lateral irrigation evaluation.

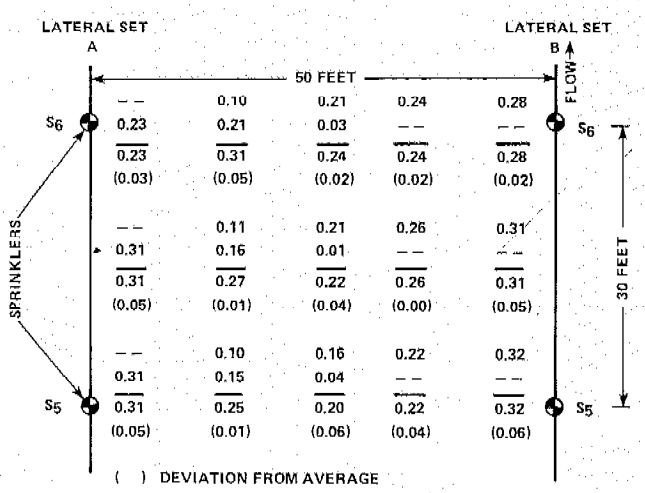


Figure 11-25.—Combined catch pattern in inch per hour between sprinklers 5 and 6 for a 50-ft lateral spacing.

of ±1 to 2 percent. In addition, the normal variation of the uniformity values can be approximated by:

$$\pm[0.2\ (100 - CU)]\%;\ \text{or}\ \pm[0.2\ (100 - DU)]\%$$

Nozzle discharge varies with the nozzle pressure unless special flexible orifice nozzles are used to control the flow. Figure 11-26 shows the relationship between discharge and pressure for a typical fixed 5/32-in nozzle that gives 5 gpm at 48 psi and for a flexible orifice nozzle designed to give 5 gpm, regardless of pressure. Unfortunately, it is difficult to manufacture the flexible orifice nozzles precisely, and they are apt to have up to ±5 percent variation in flow even with uniform pressures. The same variation is also typical for almost all the flow or pressure control devices that can be used at the base of each sprinkler. Therefore, unless the difference in pressures throughout the system is expected to exceed 25 percent of the desired average operating pressure, it is best to use standard fixed nozzles and no flow-control devices.

The flexible orifice nozzles maintain constant flow without causing a pressure drop of at least 10 to 15 psi, which is typical of the flow or pressure control devices used at the base of sprinklers. This is an important advantage when operating pressures are lower than 50 psi and maintaining a reasonably high nozzle pressure is necessary to have adequate jet breakup and range of throw. However, when pressures are above 80 psi, the jet breakup and

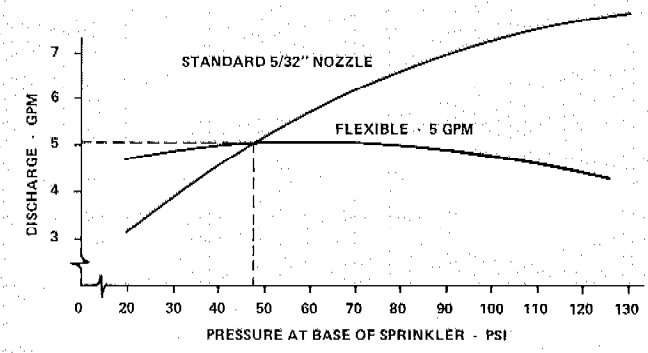


Figure 11-26.—Comparison of pressure versus discharge relationship for a standard fixed nozzle and a special flexible orifice nozzle.

wind drift may be excessive and the sprinklers may turn erratically. Therefore, for such high pressure operation, pressure control devices should be used at the base of the sprinklers.

When flexible orifice nozzles are used, the DU and CU test values should be multiplied by approximately 0.95 to obtain the system uniformities. When they are not used, the pressure variations throughout the system cause the overall uniformity of the system to be lower than the uniformity in the test area. An estimate of the system DU and CU can be computed from the maximum, minimum, and average system pressures by:

$$\text{System DU} = DU \times \left(1 - \frac{P_x - P_n}{5\ P_a}\right) \quad \textbf{(11-11a)}$$

and

$$\text{System CU} = CU \times \left(1 - \frac{P_x - P_n}{8\ P_a}\right) \quad \textbf{(11-11b)}$$

where

P_x = the maximum sprinkler pressure (psi)
P_n = the minimum sprinkler pressure (psi)
P_a = the average sprinkler pressure (psi)

Using the data from figure 11-24, part 12 with the test DU = 82%:

$$\text{System DU} = 82 \times \left(1 - \frac{45 - 39}{5 \times 40}\right) = 80\%$$

and with the test CU = 87%:

$$\text{System CU} = 87 \times \left(1 - \frac{45 - 39}{8 \times 40}\right) = 85\%$$

The leading manufacturers of sprinklers are continually field testing their products, and data are available on several sprinklers operating under various field conditions. When planning sprinkle irrigation systems, request such data from the distributors or manufacturers. If available, the data should be used as a basis for selecting the combination of spacing, discharge, nozzle size, and operating pressure that will result in the highest practical uniformity coefficient for the existing operating conditions.

Spacing.—The basic criterion governing the selection of spacing for any given sprinkler nozzle-pressure and wind combination is the uniformity of distribution desired. In general, a CU of about 85 percent is recommended for delicate and shallow-rooted crops such as potatoes and most other vegetables. A CU above 75 percent is generally adequate for deep-rooted field crops such as alfalfa, corn, cotton, and sugar beets. Tree and vine crops that have deep spreading root systems can be adequately irrigated if the CU is above 70 percent. When applying chemicals through the system, however, a CU above 80 percent is recommended. When systems have low CUs due to wind, chemicals should be applied only during calm periods.

Table 11-7 gives a more useful meaning to the concept of CU. From table 11-7, if a sprinkle system has a CU of 86 percent, for each inch of gross application received by the crop or soil, 80 percent of the area would receive at least 0.85 in. If the CU were only 70 percent, 80 percent of the area would receive at least 0.68 in. To apply a net application of 1.0 in to at least 80 percent of the area with a system having a CU of 86 percent, a gross of 1.0 divided by 0.85 = 1.18 in plus wind drift and evaporation losses must be applied. With a CU of only 70 percent, a gross after drift and evaporation losses of 1.0 divided by 0.68 = 1.47 in would be required.

Figure 11-27 illustrates the relation between rainfall area and depth of water applied at the CU values discussed above. Both 70 and 86 percent CU values leave 20 percent of the area underirrigated, and 80 percent of the area adequately or overirrigated. However, this requires a gross application of approximately 25 percent more water with the 70 percent CU than with the 86 percent CU. Data for constructing figure 11-27 were taken from table 11-7.

Table 11-7.—Minimum depth of water applied per 1.0 in gross application for various values of CU and percentages of land area adequately irrigated

CU percent	Percent of area adequately irrigated							
	95	90	85	80	75	70	65	60
	(inch)							
90	0.79	0.84	0.87	0.89	0.92	0.93	0.95	0.97
86	.71	.78	.82	.85	.88	.91	.93	.96
82	.63	.71	.77	.81	.85	.88	.91	.94
78	.55	.65	.71	.77	.81	.86	.89	.93
74	.46	.58	.66	.73	.78	.83	.88	.92
70	.38	.52	.61	.68	.75	.80	.86	.91

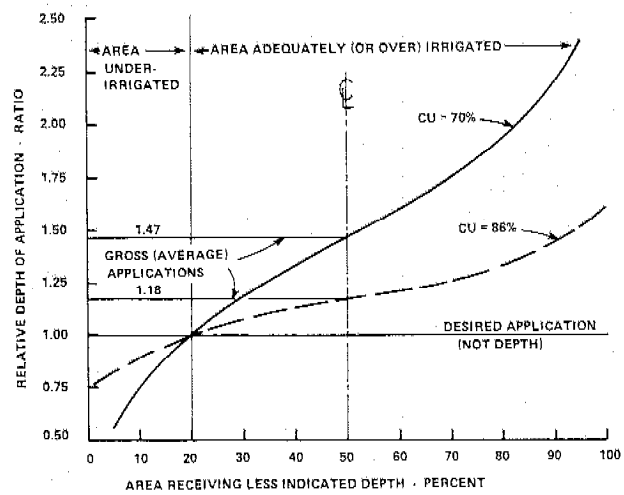


Figure 11-27.—Relationships between surface area and depth of water applied for CU values of 70 and 86 percent when 20 percent of the area is underirrigated and the remaining 80 percent of the area is adequately (or over) irrigated.

When any given CU value is used as the irrigation application efficiency, the area adequately irrigated will be approximately 80 percent, i.e., note that the values under the 80 percent adequacy column correspond almost perfectly with the values under the CU column.

When three or more adjacent laterals are operated simultaneously in a fixed or block-move system, the wind drift and evaporation losses are minimized and essentially all of the water is applied effectively. Therefore, table 11-7 can be used to approximate overall irrigation efficiency for "block system" layouts.

Table 11-8 gives a better understanding of CU and shows the relative productivity, especially when dealing with shallow-rooted vegetative crops

such as forage crops. According to table 11-8, almost optimum yields may be obtained with a system having a low CU. For example, with a CU of 90 percent and 90 percent of the area adequately irrigated, 99 percent of optimum yield might be obtained by applying gross irrigations of 1.19 times the adjusted net requirements after allowing for wind drift and evaporation losses (fig. 11-17). With a CU of only 70 percent, 97 percent of the optimum yields might be obtained if 90 percent of the area were adequately irrigated. The gross irrigation requirements, however, would be 1.92 times the adjusted net requirement. If only 1.19 times the adjusted net were applied only 65 percent of the area would be adequately irrigated (table 11-7) and only 90 percent of optimum yields might be expected (table 11-8).

Table 11-8.—Relative percentages of optimum productivity (where overwatering does not reduce yields) for various values of CU and percentages of land area adequately irrigated

CU	Percent of area adequately irrigated							
percent	95	90	85	80	75	70	65	60
90	100	99	99	98	98	97	97	96
86	100	99	98	98	97	96	96	95
82	99	99	98	97	96	95	94	93
78	99	98	97	96	95	94	93	91
74	98	97	96	95	94	93	91	90
70	98	97	95	94	92	91	90	88

For preliminary design purposes, tables 11-9 through 11-12 may be used as a guide for estimating the anticipated CU for various sprinkler spacing and application rate combinations. The CU estimates presented in the tables were derived from an analysis of numerous tests of impact sprinklers having 1/2- or 3/4-in bearings, standard 22° to 28° trajectory angles, and nozzles without vanes. The tables are separated into four sections according to wind speeds (up to 4 mph, 4 to 10 mph, 10 to 15 mph, and 15 to 20 mph). Using vanes or angles from 18° to 21° may improve uniformities in the higher wind speeds, and under these conditions table 11-10 can be used for 10-15 mph winds or table 11-11 can be used with caution for 15-20 mph winds.

The nozzle sizes and pressures given in the tables for each spacing will give application rates (I) that fall within 0.02 iph of rates indicated by the column headings. Equation 2 should be used to compute the precise flow rate needed for a given I and the manufacturer's sprinkler tables used to determine the required operating pressure. Pressures for standard nozzles should be selected to fall within the following ranges.

Nozzle sizes	Pressure range[1]
-inch-	-psi-
5/64 to 3/32	20 - 45
7/64 to 9/64	25 - 50
5/32 to 11/64	30 - 55
3/16 to 7/32	35 - 60

[1] When straightening vanes are used, add 5 psi.

The low side of the pressure ranges given above should be increased by 5 to 10 psi when sprinkling bare soils that tend to seal. High pressures should be avoided to save energy and eliminate excessive drift and evaporation losses.

Risers.—Straight riser pipe, located between the sprinkler head and the lateral line pipe, must be provided in order to remove the turbulence set up when the direction of flow is changed by diversion of a part of the flow to an individual sprinkler. If not removed, this turbulence will carry through the nozzle and cause a premature stream breakup, a reduced diameter of coverage, and hence a poorer distribution pattern. The length of pipe needed to remove turbulence varies with sprinkler discharge. Recommended *minimum* riser lengths follow:

Discharge, gpm	Risers	Discharge, gpm	Risers
Under 10	6-inch	50-120	18-inch
10-25	9-inch	more than 120	36-inch
25-50	12-inch		

Most crops exceed 12 in. in height so, except for clean cultivated orchards where low riser pipes are desirable for under-tree sprinkling, the choice will be the minimum height to clear the crop. Although some research studies indicate that 12 to 24 in additional height improve the sprinkler distribution efficiency, there are obvious disadvantages such as wind drift and awkward handling of the lateral line. Farmers usually prefer 18- to 24-inch risers except when irrigating high-growing crops such as cotton and corn.

Discharge Requirement.—The required average discharge (q) of each sprinkler is a function of the water application rate (I) and the sprinkler spacing.

Table 11-9.—A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under low wind conditions (0 to 4 mph)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	9/64×3/32
30 × 40	Pressure, psi	30	50	45	45	45	40	40
	CU, %	82	83	82	83	83	85	88
	Nozzle, inch	3/32	7/64	1/8	9/64	5/32	11/64	11/64
30 × 50	Pressure, psi	40	40	45	50	45	45	50
	CU, %	83	88	86	86	84	85	86
	Nozzle, inch		1/8	9/64	5/32	11/64	3/16	3/16
30 × 60	Pressure, psi		40	45	45	45	45	50
	CU, %		88	88	89	88	85	87
	Nozzle, inch	7/64	1/8	9/64	1/8×3/32	5/32×3/32	5/32×3/32	5/32×1/8
40 × 40	Pressure, psi	30	35	35	40	35	40	35
	CU, %	78	82	86	87	88	89	90
	Nozzle, inch			5/32	5/32×3/32	5/32×3/32	11/64×3/32	3/16×3/32
40 × 50	Pressure, psi			35	35	45	40	40
	CU, %			78	83	84	88	89
	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
40 × 60	Pressure, psi			50	50	50	50	50
	CU, %			83	85	85	84	86
	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
60 × 60	Pressure, psi			60	65	65	80	88
	CU, %			88	88	88	88	88

Table 11-10.—A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under moderate wind conditions (4-10 mph)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	9/64x3/32
30 × 40	Pressure, psi	30	50	45	45	45	40	40
	CU, %	82	85	85	82	83	84	85
	Nozzle, inch	3/32	7/64	1/8	9/64	5/32	11/64	11/64
30 × 50	Pressure, psi	40	40	45	50	45	45	50
	CU, %	70	75	84	84	84	87	85
	Nozzle, inch		1/8	9/64	5/32	11/64	3/16	3/16
30 × 60	Pressure, psi		40	45	45	45	45	50
	CU, %		80	84	84	84	85	86
	Nozzle, inch	7/64	1/8	9/64	1/8x3/32	5/32x3/32	5/32x3/22	5/32x1/8
40 × 40	Pressure, psi	30	35	35	40	35	40	35
	CU, %	80	83	83	83	84	87	86
	Nozzle, inch			5/32	5/32x3/32	5/32x3/32	11/64x3/32	3/16x3/32
40 × 50	Pressure, psi			35	35	45	40	40
	CU, %			76	76	76	83	84
	Nozzle, inch			4/32	11/64	3/16	13/64	7/32
40 × 60	Pressure, psi			50	50	50	50	50
	CU, %			77	81	83	84	85
	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
60 × 60	Pressure, psi			60	65	65	80	68
	CU, %			80	82	83	84	84

Table 11-11.—A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under high wind conditions (10-15 mph)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
30 × 40	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	5/32
	Pressure, psi	30	50	45	45	45	40	45
	CU, %	75	80	80	84	84	85	86
30 × 50	Nozzle, inch		7/64	1/8	9/64	5/32	11/64	11/64
	Pressure, psi		40	45	50	45	50	55
	CU, %		70	81	82	87	88	88
30 × 60	Nozzle, inch			9/64	5/32	11/64	3/16	3/16
	Pressure, psi			45	45	45	45	50
	CU, %			72	75	81	84	86
40 × 40	Nozzle, inch		1/8	9/64	5/32	11/64	11/64	3/16
	Pressure, psi		35	35	35	35	50	45
	CU, %		80	82	81	80	86	85
40 × 50	Nozzle, inch			5/32	5/32	11/64	3/16	13/64
	Pressure, psi			35	50	50	50	50
	CU, %			77	78	80	80	82
40 × 60	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
	Pressure, psi			50	50	50	50	50
	CU, %			68	74	78	81	82
60 × 60	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
	Pressure, psi			60	65	65	80	68
	CU, %			64	66	68	80	82

Table 11-12.—A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under extreme wind conditions (15-20 mph)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
30 × 40	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	5/32
	Pressure, psi	30	50	45	45	45	40	45
	CU, %	69	72	73	75	76	82	85
30 × 50	Nozzle, inch			1/8	9/64	5/32	11/64	11/64
	Pressure, psi			45	50	45	50	55
	CU, %			74	77	80	81	84
30 × 60	Nozzle, inch			9/64	5/32	11/64	3/16	3/16
	Pressure, psi			45	45	45	45	50
	CU, %			60	65	75	80	83
40 × 40	Nozzle, inch			9/64	5/32	11/64	11/64	3/16
	Pressure, psi			35	35	35	50	45
	CU, %			70	72	76	81	84
40 × 50	Nozzle, inch			5/32	5/32	61/64	3/16	13/64
	Pressure, psi			35	50	50	50	50
	CU, %			55	60	70	75	77
40 × 60	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
	Pressure, psi			50	50	50	50	50
	CU, %			64	70	73	74	75
60 × 60	Nozzle, inch						7/32	1/4
	Pressure, psi						80	68
	CU, %						66	75

The desired I depends on time per set, net depth to be applied per irrigation, and application efficiency. It is practical to change periodic-move laterals only once or twice per day unless they are automated. For one change per day, the time per set will be 24 hr minus the length of time required to change the lateral position, leaving a total of 23 to 23.5 hr. For two changes per day, set times will range between 11 and 11.5 hr.

Figure 11-28 shows a copy of figure 11-13 completed for a sample field of alfalfa and potatoes. Sample calculations 11-3 and 11-4 illustrate the procedure for determining the desired application rate (I) and related average sprinkle discharge (q) for the alfalfa field and the potato field, respectively.

Sample calculation 11-3.—Determine the net depth per irrigation, irrigation interval, irrigation efficiency, application rate, and sprinkler discharge requirement.

Given:

The information in parts I and II of figure 11-28 for alfalfa

An average wind of 4-10 mph

Assume:

The soil moisture depletion is MAD = 50%

There will be one change per day

The sprinkler spacing is 40 × 60 ft

Calculation:

For a MAD = 50%, the allowable soil water depletion is 50 percent of the total available water-holding capacity of the root zone which in this case is:

$$6 \text{ ft} \times 2.0 \text{ in/ft} \times \frac{50}{100} = 6.0 \text{ in}$$

The maximum allowable irrigation interval during the peak use period is

$$\frac{\text{allowable depletion (in)}}{\text{water use rate (in/day)}} = \frac{6.0}{0.30} = 20 \text{ days}$$

These are the maximum allowable depletion and corresponding maximum interval during the peak use period that will give the desired level of productivity. To fit the final system design, lesser net applications and correspondingly shorter intervals may be used.

The application efficiency can be estimated from the effective portion of the applied rate (R_e) and the uniformity of application. Assuming the spray will be midway between coarse and fine (from fig. 11-18) for a potential evapotranspiration rate of 0.3 in/day the effective portion, $R_e = \frac{(0.97 + 0.91)}{2} = 0.94$.

Because alfalfa is a relatively low value crop, an applied efficiency (E_h) based on the average low-half depth is appropriate, i.e., use CU. Assuming an E_h of 75 percent, the gross application would be:

$$\frac{6.0}{75/100} = 8.0 \text{ in}$$

Assuming it will take 1 hour to change the position of a hand-move lateral, the time per set with one change per day will be 23 hr. Thus the preliminary application rate is:

$$I' = \frac{8.0 \text{ in}}{23 \text{ hr}} = 0.35 \text{ iph}$$

From table 11-10 (4-10 mph winds) the anticipated CU = 84% on a 40- x 60-ft spacing and 0.34 iph. A more specific estimate of CU can often be obtained directly from a supplier. The expected application efficiency can now be estimated by equation 8:

$$E_h = CU \times R_e = 84 \times 0.94 = 79\%$$

The required gross application can now be more accurately computed as:

$$\frac{6.0}{79/100} = 7.6 \text{ in}$$

and the required application rate is:

$$I = \frac{7.6 \text{ in}}{23 \text{ hr}} = 0.33 \text{ iph}$$

The required sprinkler discharge can now be calculated by equation 2:

$$q = \frac{I \times S_f \times S_m}{96.3}$$

$$= \frac{0.33 \times 40 \times 60}{96.3} = 8.22 \text{ gpm}$$

I.	Crop (type)	*Alfalfa*	*Potatoes*	
	(a) Root depth (ft)	*6*	*2.5*	*Table 11-2*
	(b) Growing season (days)	*165*	*135*	*From*
	(c) Water use rate (in/day)	*0.30*	*0.25*	*Irrigation*
	(d) Seasonal water use (in)	*30.0*	*19.0*	*Guide*
II.	Soils (area)			
	(a) Surface texture Depth (ft) Moisture capacity (in/ft)	*Loam* *8* *2.0*	*Sandy loam* *4* *1.6*	*Table 11-1*
	(b) Subsurface texture Depth (ft) Moisture capacity (in/ft)			
	(c) Moisture capacity (in)	*12.0*	*4.0*	
	(d) Allowable depletion (in)	*6.0*	*2.0*	*(50% of total)*
	(e) Intake rate (iph)	*0.6*	*0.4*	*Table 11-4*
III.	Irrigation			
	(a) Interval (days)	*20*	*8*	
	(b) Net depth (in)	*6.0*	*2.0*	
	(c) Efficiency (%)	*79*	*75*	
	(d) Gross Depth (in)	*7.6*	*2.7*	
IV.	Water Requirement			
	(a) Net seasonal (in)	*30*	*19*	
	(b) Effective rain (in)	*3*	*2*	
	(c) Stored moisture (in)	*5*	*2*	
	(d) Net irrigation (in)	*22*	*15*	
	(e) Gross irrigation (in)	*28*	*20*	
	(f) Number of irrigations	*3 to 4*	*7 to 8*	
V.	System capacity			
	(a) Application rate (iph)	*0.33*	*0.23*	
	(b) Time per set (hrs)	*23*	*11.5*	
	(c) Settings per day	*1*	*2*	
	(d) Days of operation per interval	*18*		
	(e) Preliminary system capacity (gpm)			

Figure 11-28.—Preliminary sprinkler irrigation system design factors.

Sample calculation 11-4.—Determine irrigation efficiency and application rate.

Given:

The information in parts I and II of figure 11-28 for potatoes.

An average wind of 10-15 mph

Assume:

The soil moisture depletion is MAD = 50%

Side-roll laterals will be used and two changes per day will be made.

The sprinkler spacing is 40 x 50 ft

Calculation:

Determine R_e = 0.92 from figure 11-17 for ET = 0.25 in/day for 10-15 mph wind and average spray. Because potatoes are a relatively high-value, shallow-rooted crop, an application efficiency (E_q) based on the average low-quarter depth, is appropriate, so use DU as the measure of uniformity. This will leave approximately 10 percent of the area underwatered. Assuming an E_q of 67 percent the gross application would be:

$$\frac{2.0}{67/100} = 3.0 \text{ in}$$

Assuming it will take 30 min to change the position of a side-roll lateral, the time per set with two changes per day will be 11.5 hr. Thus the preliminary application rate is:

$$I' = \frac{3.0 \text{ in}}{11.5 \text{ hr}} = 0.26 \text{ iph}$$

From table 11-11, (10-15 mph winds) the anticipated CU =78%. If alternate sets are used the improved CU_a can be estimated by equation 6a as:

$$CU_a = 10\sqrt{CU} = 10\sqrt{78} = 88\%$$

These are two processes that can be used to develop the expected E_q. An estimated DU_a can be determined by equation 5b as:

$$DU_a = 100 - 1.59\,(100 - CU_a)$$
$$= 100 - 1.59\,(100 - 88) = 81\%$$

and from equation 9:

$$E_q = 81 \times 0.92 = 75\%$$

The other method is to use table 11-7 with CU_a = 88% and find that for 90 percent of the area adequately irrigated 0.81 in is the minimum depth of water applied per 1.0 in of effective application so:

$$E_{(90\% \text{ adequate})} = 0.81 \times 0.92 = 75\%$$

Obviously, if alternate sets had not been used the efficiency would have been much lower, i.e., about 60 percent for 90 percent adequacy. Also, if an efficiency of 75 percent is assumed and alternate sets are not used, the area adequately irrigated will only be 75 percent. This was determined by noting that 0.81 in is the minimum depth of water applied per 1.0 in of effective application with a CU of 78 percent and 75 percent adequacy in table 11-7.

The required gross application, assuming E_q = 75%, can now be determined as:

$$\frac{2.0}{75/100} = 2.7 \text{ in}$$

and the required application rate is:

$$I = \frac{2.7 \text{ in}}{11.5 \text{ hr}} = 0.23 \text{ iph}$$

The required sprinkler discharge can now be computed by equation 2 as:

$$q = \frac{0.23 \times 40 \times 50}{96.3} = 4.78 \text{ gpm}$$

The production value of having 90 percent adequacy by using alternate sets vs. 75 percent adequacy can be demonstrated, assuming overwatering does not reduce yields. Table 11-8 gives relative percentages of optimum production for different CU and adequacy values. With a CU = 78% and 75 percent adequacy, the relative production is 95 percent and for a CU = 88% and 90 percent adequacy, it is 99 percent. Thus the use of alternate sets can be expected to improve yields by at least 4%. If, however, uneven watering decreases production or quality (due to leaching of fertilizer or waterlogging), the gross income differences may be considerably larger than 4 percent.

Nozzle Size and Pressure.—Table 11-13 is a list of the expected discharge and wetted diameters in conditions of no wind from typical 1/2- and 3/4-in bearing impact sprinklers with angles of trajectory between 22° and 28° and having standard nozzles

Table 11-13.—Nozzle discharge and wetted diameters for typical 1/2- and 3/4- inch bearing impact sprinklers with trajectory angles between 22° and 28° and standard nozzles without vanes [1]

Sprinkler pressure	Nozzle diameter—inch																	
	3/32		7/64		1/8		9/64		5/32		11/64		3/16		13/64		7/32	
psi	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft
20	1.14	63	1.55	73														
25	1.27	64	1.73	76	2.25	76	2.88	79	3.52	82		[2]						
30	1.40	65	1.89	77	2.47	77	3.16	80	3.85	85	4.64	88	5.50	91	6.50	94	7.58	96
35	1.51	66	2.05	77	2.68	78	3.40	81	4.16	87	5.02	90	5.97	94	7.06	97	8.25	100
40	1.62	67	2.20	78	2.87	79	3.64	82	4.45	88	5.37	92	6.40	96	7.55	99	8.82	102
45	1.72	68	2.32	79	3.05	80	3.85	83	4.72	89	5.70	94	6.80	98	8.00	101	9.35	104
50	1.80	69	2.45	80	3.22	81	4.01	84	4.98	90	6.01	95	7.17	100	8.45	103	9.88	106
55	1.88	70	2.58	80	3.39	82	4.25	85	5.22	91	6.30	96	7.52	101	8.85	104	10.34	107
60	1.98	71	2.70	81	3.54	83	4.42	86	5.45	92	6.57	97	7.84	102	9.24	105	10.75	108
65					3.68	84	4.65	87	5.71	93	6.83	98	8.19	103	9.60	106	11.10	109
70					3.81	84	4.82	88	5.92	94	7.09	99	8.49	104	9.95	107	11.40	110
K_d [3]	0.255		0.346		0.453		0.575		0.704		0.849		1.012		1.193		1.394	

[1] The use of straightening vanes or special long discharge tubes increases the wetted diameter by approximately 5%.
[2] Lines represent upper and lower recommended pressure boundaries.
[3] $q = K_d\sqrt{P}$.

without vanes. The various values in the table are for different nozzle sizes between 3/32- and 7/32-in and base of sprinkler pressures between 20 and 70 psi.

In general the relationship between discharge and pressure from a sprinkler can be expressed by the orifice equation:

$$q = K_d \sqrt{P} \qquad \textbf{(11-12)}$$

where

q = the sprinkler discharge (gpm)
K_d = the discharge coefficient for the sprinkler and nozzle combined
P = the sprinkler operating pressure (psi)

The K_d can be determined for any combination of sprinkler and nozzle if a P and a corresponding q are known. Because of internal sprinkler friction losses, K_d decreases slightly as q and P increase; however, over the normal operating range of most sprinklers it can be assumed to be constant. The average values of K_d over the recommended range of operating pressures for each nozzle size are given in table 11-13.

Equation 12 can be rearranged to give:

$$q = q' \sqrt{P/P'} \qquad \textbf{(11-13a)}$$

or

$$P = P'(q/q')^2 \qquad \textbf{(11-13b)}$$

where the P' and q' are corresponding values that are known (from table 11-13 or a manufacturers table) and either q or P is not known.

Sample calculation 11-5 illustrates the procedure for determining the nozzle size and pressure required to obtain a given sprinkler discharge.

Sample calculation 11-5.—Determination of nozzle size and average operating pressure.

Given:

The sprinkler spacing of 40- by 60-ft and the average sprinkler discharge of q_a = 8.22 gpm for the alfalfa field considered in sample calculation 11-3.

Calculation:

From table 11-10, a sprinkler with a 13/64-in nozzle should be appropriate (see 0.35 ± 0.02 iph). Furthermore, from table 11-13 or from appropriate manufacturers charts, a 13/64-in nozzle will discharge 8.00 gpm at 45 psi and 8.44 gpm at 50 psi. Thus the average sprinkler pressure (P_a) which will give the required discharge can be interpolated as P_a = 47 psi.

Another way to estimate P_a is by equation 13.

$$P_a = 45 \left(\frac{8.22}{8.00}\right)^2 = 47 \text{ psi}$$

or by equation 12

$$P_a = \left(\frac{q_a}{K_d}\right)^2 = \left(\frac{8.22}{1.193}\right)^2 = 47 \text{ psi}$$

System Layout

Figure 11-29 shows general types of periodic-move sprinkle system layouts. Often the layout of a system will be simple, as in the case of small regularly shaped areas. On the other hand, large odd-shaped tracts with broken topography may present a complex engineering problem requiring alternate layouts and careful pipe-size analyses. The following paragraphs discuss the most important points that must be considered in planning a system layout and the general rules to follow. These rules provide only general guidance to the planner. In the more complex layouts, considerable judgment must be exercised.

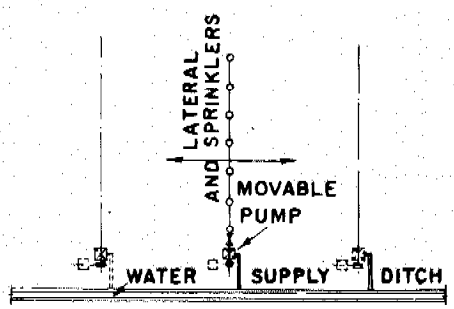
Number of Sprinklers Operated.—A system layout must provide for simultaneous operation of the average number of sprinklers that will satisfy the required system capacity determined by equation 1. This average number is computed as follows:

$$N_n = \frac{Q}{q_a} \qquad \textbf{(11-14a)}$$

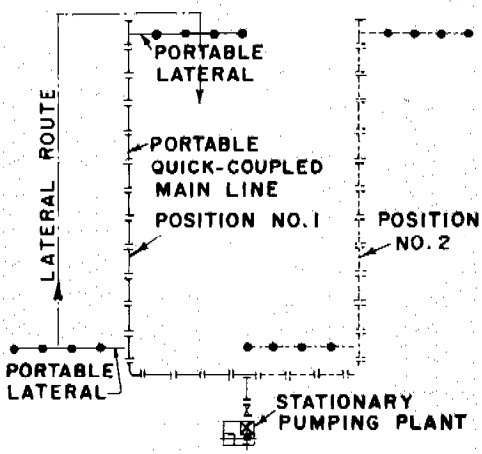
where

N_n = minimum average number of sprinklers operating
Q = system capacity from equation 1 (gpm)
q_a = average sprinkler discharge (gpm)

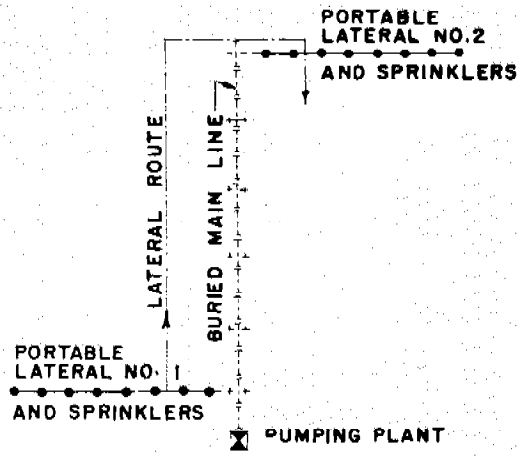
The variation in the number of sprinklers operated from time to time during an irrigation should be kept to a minimum to facilitate lateral routing



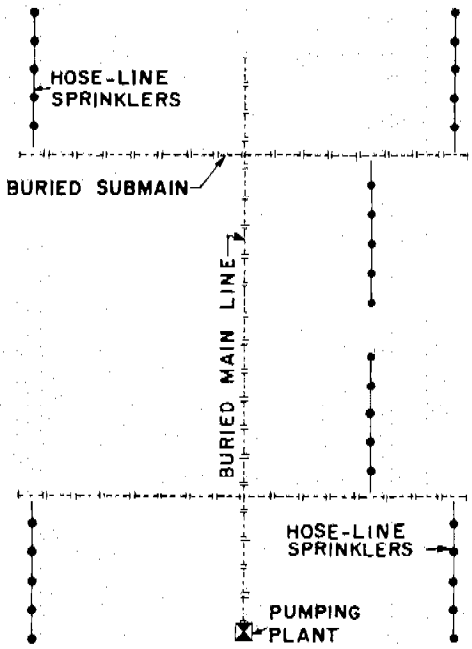
A—Fully portable sprinkler system with portable lateral and movable pumping plant.



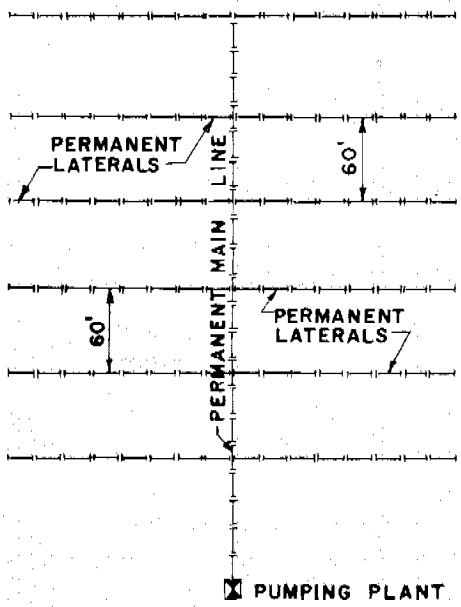
B—Portable laterals and main lines with stationary pumping plant.



C—Portable laterals, permanent buried main line, and stationary pumping plant.



D—Permanent mains and submains with portable hose lines.



E—Permanent main lines and laterals with movable or permanent sprinklers and quick-coupled riser pipes.

Figure 11-29.—General types of periodic-move sprinkle systems.

and to maintain a nearly constant load on the pumping plant. Because no variation will be needed in a rectangular area, farmers should be encouraged to relocate fences, drainage ditches, roads, and other field boundaries, where practicable, to obtain a rectangular area.

Pipe lengths are generally standardized, and sprinklers on portable systems are normally spaced at 30-, 40-, and 60-ft intervals on the laterals. Furthermore, the spacing between laterals is usually at 40-, 50-, 60-, and 80-ft intervals along the mainline. Since whole laterals must be operated simultaneously, the preliminary system capacity determined by equation 1 may be lower than the required capacity even on rectangular fields. However, the depth per irrigation (d) or the length of actual operating time per irrigation (f $\times$ T) can usually be adjusted to optimize the fit.

On odd-shaped fields where it is sometimes necessary to operate less than the average required number of sprinklers for one or more lateral settings, the engine is throttled down to reduce the discharge. Where two or more laterals (each containing different numbers of sprinklers) are operating simultaneously, valves in the lateral lines must be used to control the pressure at the sprinklers. For most odd-shaped tracts, the number of sprinklers needed will exceed the theoretical minimum number computed, and extra equipment will be necessary to serve parts of the tract most distant from its center.

If the design area is subdivided, the number of sprinklers required for each subdivision must be computed separately.

Number of Lateral Settings.—The number of settings required for each lateral depends on the number of allowable sets per day and on the maximum number of days allowed for completing one irrigation during the peak-use period (f). The required number of settings per lateral must not exceed the product of these two factors.

If the system layout provides for at least the theoretical minimum number of sprinklers required, then the number of settings required per lateral will not exceed this allowable limit. Long, narrow, or irregularly shaped parts of a tract, however, may require additional lateral settings. Thus, more equipment is necessary if such areas are to be served within the allowable time period.

Lateral Layout.—Figure 11-30 shows the effects of topography on lateral layout. To obtain near-uniform application of water throughout the length of a lateral, the line must be of a pipe diameter and length and follow an alignment that will result in a minimum variation in the discharge of individual sprinklers along the line. Normally this variation in discharge should not exceed 10 percent unless long term economic justification exists. Therefore, either pressure (or flow) regulation must be provided for each sprinkler or laterals must be located and pipe sizes selected so that the total losses in the line, due to both friction head and static head, *will not exceed 20 percent of the average design operating pressure* for the sprinklers (P_a).

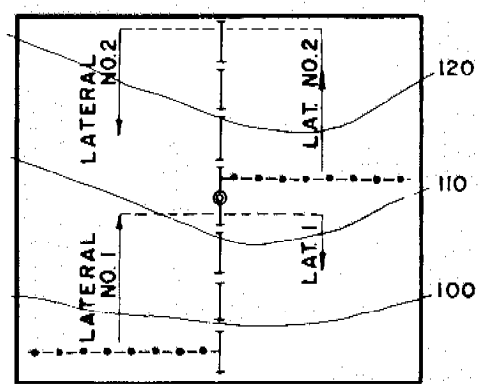
To meet this pressure-variation criteria, it is usually necessary to lay laterals across prominent land slopes (fig. 11-30A and B). Laid on level land or on the contour, a lateral of a given pipe size with a fixed average sprinkler-discharge rate (q_a) will thus be limited only to that length in which 20 percent of P_a is lost as a result of friction.

Running laterals uphill should be avoided wherever possible. Where they must be used, they need to be materially shortened unless pressure or flow regulators are used. Such a lateral of a given pipe size and fixed q_a is limited to that length in which the loss due to friction is equal to the difference between 20 percent of P_a and the loss due to static head. For example, if the static head caused by the difference in elevation between ends of the lateral amounts to 12 percent of P_a, then the line is limited to the length in which only 8 percent of P_a is lost because of friction.

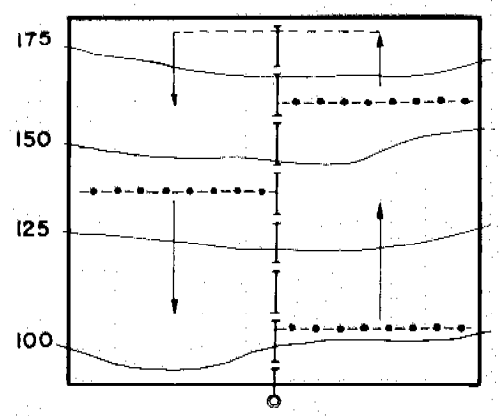
Running laterals downslope is often a distinct advantage, provided the slope is fairly constant and not too steep (see fig. 11-30C, D, E, and F). Because the difference in elevation between the two ends of the line causes a gain in head, laterals running downslope may be longer than lines laid on level ground.

While downslopes may permit longer laterals for a given pipe size or smaller pipe for a given length of lateral, such a layout does not usually permit split-line layout and lateral rotation about the mainline or submain. Thus labor costs may be higher.

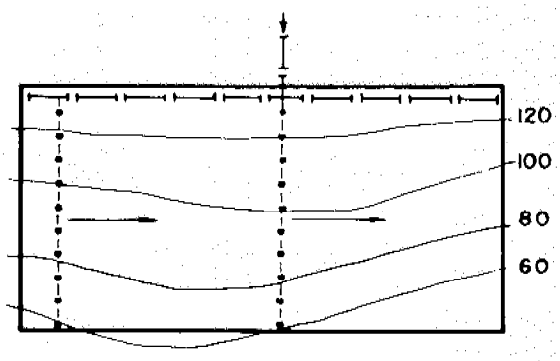
When the slope of the ground along the lateral is about equal to the slope of the friction loss, the pressure along the lateral is nearly constant. When the slope along the lateral increases for successive settings, intermediate control valves may be required to avoid building up excessive pressures and exceeding the variation limit.



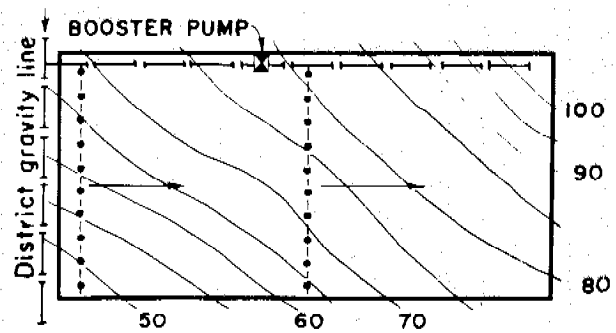
A-Layout on moderate, uniform slopes with water supply at center.



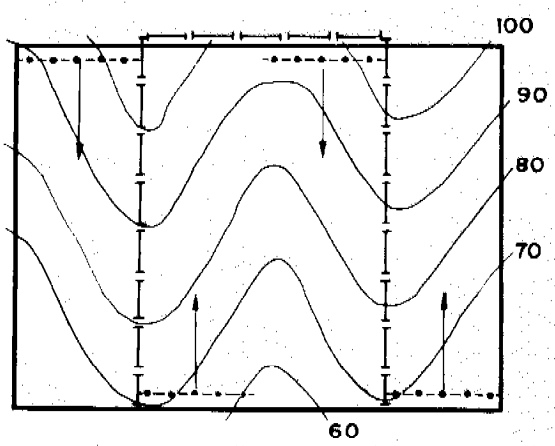
B-Layout illustrating use of odd number of laterals to provide required number of operating sprinklers.



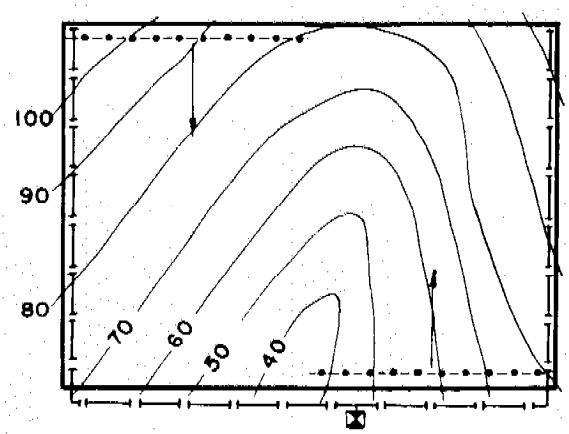
C-Layout with gravity pressure where pressure gain approximates friction loss and allows running lateral downhill.



D-Layout illustrating area where laterals have to be laid downslope to avoid wide pressure variation caused by running laterals upslope.



E-Layout with two main lines on ridges to avoid running laterals uphill.



F-Layout with two main lines on the sides of the area to avoid running the laterals uphill.

Figure 11-30.—Layouts of periodic-move sprinkle systems showing effects of topography on laterals.

Hand-move lateral lines need to be limited to one or two pipe sizes for simplicity of operation. The trend in recent years has been toward the use of a single pipe size.

Lateral lines should be located at right angles to the prevailing wind direction where possible and moved in the direction of the wind if the water contains more than 1000 ppm of salts.

If lateral pipelines are to remain in a single design area and are not to be moved from field to field, they should be located so that they can be rotated around the mainline, thereby minimizing the hauling of pipe back to the starting point for subsequent irrigations (see fig. 11-29C).

Farming operations and row directions often influence the layout of laterals. Contoured row crops can be sprinkle irrigated only with hand-move or solid-set systems, which presents special problems such as difficulty in placing and moving lateral lines and getting uniform coverage.

Where the land is terraced and the topography broken, curves in the alignment of the rows may be sharper than can be turned with the limited deflection angle of the coupling devices on portable irrigation pipe. This difficulty may be overcome in the following ways: soil profiles permitting, land grading may be used to improve terrace and row alignment; short lengths of flexible hose may be used in the line at the sharpest bends. Some growers prefer to run the laterals parallel and downhill on a slope somewhat steeper than the grade of the terraces even though both rows and terraces must be crossed by the pipelines. In such cases, several plants are removed or left out of each row at points crossed by the lateral lines.

Where sloping land is terraced and the slopes are not uniform, lateral lines laid between crop rows will not be parallel. Thus the lateral spacing (S_m) will be variable between two adjacent lines. This variation adversely affects uniform application and efficient water use. Where topography permits their use, parallel terraces will help overcome this problem.

Stripcropping has been used effectively in overcoming some of the difficulties arising from sprinkle irrigation of contoured row crops. The row crops are planted in strips equal in width to the lateral spacing. The alternating strips are equal in width to the lateral spacing at the mainline point of beginning but may vary considerably in width at points distant from the mainline. Laterals are laid on the contour along the outside of the row-crop strips as shown in figure 11-31A. In this method the hay crops as well as the row crop are irrigated. Advantages of this procedure are uniform coverage on the row-crop strips and the relative ease of moving the pipe on firmer footing and outside the areas of tall crops. Disadvantages are nonuniform coverage on the secondary hay crop and the necessity for carefully laying out the strips before planting each crop.

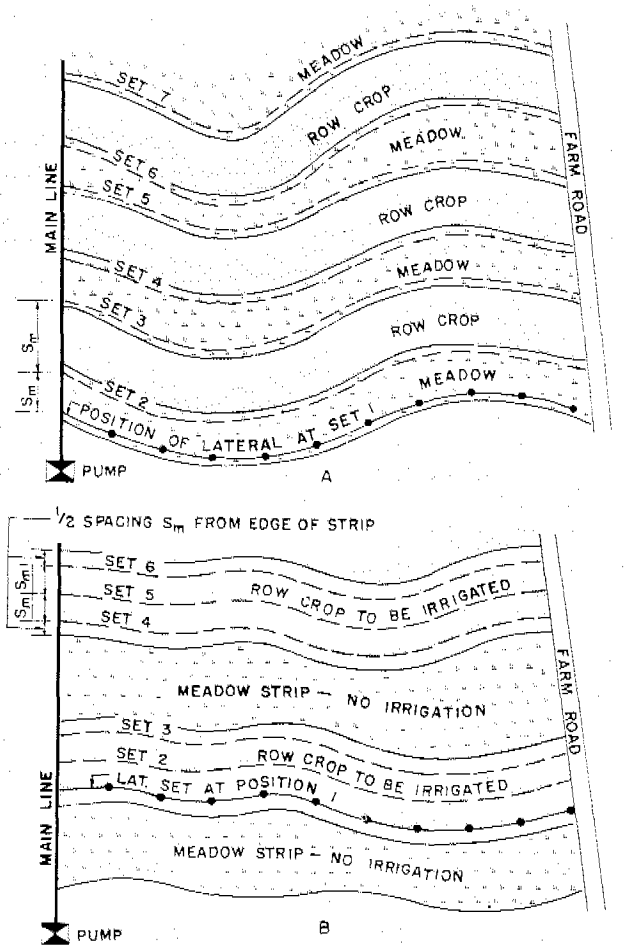


Figure 11-31.—Typical sprinkler lateral layouts on stripcropped areas.

When it is not desired to irrigate the hay crop, part-circle sprinklers may be used to irrigate the row crop alone or the row crop may be planted in strips equal in width to some multiple of S_m and the laterals operated entirely within the row-crop strips as shown in figure 11-31B. A disadvantage is in having to move the pipe when the upper part of the soil is saturated.

Perforated pipe laterals may be used when irrigating low-growing crops such as small vegetables. In

such cases, lines are laid on the contour between crop rows.

Mainline Layout.—Figures 11-29 and 11-30 show various mainline configurations. Mainlines, or submains where used, should usually run up and down predominant land slopes. Where laterals are downslope, the mainline will often be located along a ridge, with laterals sloping downward on each side.

Different pipe sizes should be used along the mainline for pressure control and to maintain a reasonably balanced load on the pumping plant.

Mainlines should be located, where possible, so that laterals can be rotated in a split-line operation as illustrated in figure 11-29C. This minimizes both pipe friction losses and the labor needed for hauling lateral pipe back to the starting point. The farmers' planting, cultural, and harvesting operations do not always permit a split-line operation, however. An example would be harvesting flue-cured tobacco over a period of several weeks while irrigation is still in progress. Water is usually applied to part of a field immediately after a priming (removing ripened leaves from the stalk), and most growers object to priming in several parts of the field simultaneously as would be necessary to stay ahead of the lateral moves in a split-line operation. The situation is similar for haying operations.

Location of Water Source and Pumping Plant.—If a choice in location of the water-supply source is possible, the source should be placed near the center of the design area. This results in the least cost for mainline pipe and for pumping. A choice of location of the water supply is usually possible only when a well is the source.

When the source is surface water, the designer must often select a location for the pumping plant. Wherever possible, the pumping plant should be located at a central point for delivery to all parts of the design area. Figure 11-12 illustrates the choice of pump locations between points A and F as follows:

With the pump at location A, line BC will carry water for 30 acres and line CF will carry water for 15 acres; with the pump at F, BC will carry water for 40 acres and CF will carry water for 72 acres. In this example, therefore, pump location A provides the least cost of mainline pipe.

On flat or gently sloping lands where water is to be pumped from gravity ditches, mainline costs will be reduced if water is run in a ditch to the center of the design area. On steeper lands, where water and pressure are obtained from a gravity line above the design area, cost is least if the gravity line enters the design area at the center of the top boundary.

Booster pumps should be considered when small parts of the design area demand higher pressures than does the main body of the system. The use of booster pumps avoids supplying unnecessarily high pressures at the main pumping plant to meet the pressure required by small fractions of the total discharge. Booster pumps are sometimes used where the static head is so great that two pumps prove more economical than a single unit. A careful analysis of pumping costs is required in such cases. Booster pumps are discussed in more detail in Chapter 8, *Irrigation Pumping Plants*.

Adjustments to Meet Layout Conditions.—After completing the layout of main lines and laterals it is usually necessary to adjust one or more of the following:

Number of sprinklers operating, N
Water-application rate, I
Gross depth of each irrigation, d
Sprinkler discharge, q_a
Spacing of sprinklers, $S_l \times S_m$
Actual operating time per day, T
Days to complete one irrigation, f
Total operating time per irrigation, $f \times T$
Total system capacity, Q

Experienced designers can foresee these adjustments during the layout process. On regular tracts, the layout can be determined early by using the *Design Procedure* presented in this chapter, and the subsequent steps developed on the basis of fixed layout requirements.

The application rate (I) can be adjusted according to the flexibility in time allowed for applying the required gross depth of water (d) but this is limited by the maximum water-application rates, determined by the water-intake rate of the soil and by the minimum water application rates practical for the design.

Since I is a function of q_a and spacing, the discharge can be modified only to the extent that the spacing or I, or both, can be modified if d is held constant. However, d and the frequency of irrigation can also be adjusted if further modification is needed. Spacing can be adjusted within limits to maintain a fixed I. Changes in spacing (S_l or S_m) can be made in 10-ft intervals to alter the number of operating sprinklers for a fixed length of lateral or the number of lateral positions across the field. Major adjustments in I to fit the requirements of a

good layout must be compensated for by modifying the operating period, f × T, to fit d.

Before the layout is made, T and f are assumed in computing Q by equation 1. If the total time of operation (T × f) is increased, Q may be proportionately reduced. The actual system capacity is the product of the maximum number of operating sprinklers (N_x and q_a). Rewriting equation 14a and replacing N_n with N_x:

$$Q = N_x \times q_a \qquad \textbf{(11-14b)}$$

Therefore, the final adjustment is to compute the total system capacity needed to satisfy maximum demands. Sample calculation 11-6 illustrates the problem of adjusting system capacity to meet layout requirements.

Sample calculation 11-6.—Determine system capacity and adjust operating conditions to meet layout requirements.

Given:

An 80-acre potato field with 1,320- by 2,640-ft dimensions

The information from figure 11-29 for potatoes and from sample calculation 11-4 gives d = 2.7 in; q_a = 4.78 gpm; 8-day irrigation interval during peak-use period; two 11.5-hr sets per day, and 40- by 50-ft sprinkler spacing.

Layout:

Preliminary system capacity by equation 1:

$$Q = \frac{453 \times Ad}{fT} = \frac{453 \times 80 \times 2.7}{8 \times 2 \times 11.5} = 532 \text{ gpm}$$

Minimum number of sprinklers by equation 14a:

$$N_n = \frac{Q}{q_a} = \frac{532}{4.78} = 112 \text{ sprinklers}$$

Design the layout with one mainline 1,320 ft long, through the center of the field with laterals 1,320 ft long to either side

With S_ℓ = 40 ft, the number of sprinklers per lateral is: 1,320/40 = 33

The minimum whole number of laterals required is: 112/33 = 4

The number of lateral settings on each side of the mainline with

S_m = 50 ft is: 1,320/50 = 27.

The number of settings for each of the 4 laterals is:

2 × 27/4 = 14 for 2 laterals and 13 for 2 laterals

Time required to complete one irrigation is: f = 14/2 = 7 days

Adjustments:

With all 4 laterals operating, the maximum number of sprinklers running is: N_x = 4 × 33 = 132 sprinklers

The time required to complete one irrigation is: f = 14/2 = 7 days

The actual system capacity computed by equation 14b is:

$$Q = N_x \times q_a = 132 \times 4.78 = 631 \text{ gpm}$$

This is higher than the preliminary capacity that was based on an 8-day irrigation interval. The final system capacity could be reduced to more nearly equal the preliminary Q = 532 gpm by letting d = 2.4 in and reducing the irrigation interval to 7 days. This would require changing q_a to about 4.25 gpm (depending on the effect on E_q). However, it was decided to leave the 8-day interval to provide a margin of safety since the water supply was sufficient. Furthermore, the savings in system costs afforded by a lower application rate would be more than offset by the added labor cost of more frequent irrigations.

Lateral Design

Lateral line pipe sizes should be chosen so that the total pressure variation in the line, due to both friction head and elevation, meets the criteria outlined in *Lateral Layout*.

Friction Losses in Laterals.—Friction loss is less for flow through a line with a number of equally spaced outlets than for flow through the length of a pipeline of a given diameter, because the volume of flow decreases each time an outlet is passed.

The method developed by Christiansen for computing pressure losses in multiple-outlet pipelines has been widely accepted and is used here. It involves first computing the friction loss in the line *without* multiple outlets and then multiplying by a

factor (F) based on the number of outlets (sprinklers in the line (N)).

The Hazen-Williams equation is commonly used for estimating the friction loss in sprinkler laterals and mainlines of various pipe materials:

$$J = \frac{h_f\ 100}{L} = 1050\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} \qquad \textbf{(11-15)}$$

where

J = head loss gradient (ft/100 ft)
h_f = head loss due to pipe friction (ft)
L = length of pipe (ft)
Q = flow rate in the pipe (gpm)
C = friction coefficient that is a function of pipe material characteristics
D = inside diameter of the pipe (in)

Typical values of C are:

Pipe	C
Plastic (4-in or larger)	150
(2- and 3-in)	140
Cement asbestos	140
Aluminum (with couplers every 30 ft)	130
Galvanized steel	130
Steel (new)	130
(15 years old)	100

Table 11-14 gives J values for portable aluminum pipe.

Christiansen's equation for computing the reduction coefficient (F) for multiple outlet pipelines where the first outlet is S_l from the mainline is:

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \qquad \textbf{(11-16a)}$$

and where the first outlet is $S_l/2$ from the mainline:

$$F = \left(\frac{2N}{2N-1}\right)\left(\frac{1}{m+1} + \frac{\sqrt{m-1}}{6N^2}\right) \qquad \textbf{(11-16b)}$$

where

m = 1.852, velocity exponent of the Hazen-Williams formula
N = number of outlets in the line.

Table 11-15 shows values of F for different numbers of outlets.

Table 11-14.—Friction loss in ft/100 ft (J) in portable aluminum pipe with 0.050-in wall and couplings every 30 ft [1]

Flow rate (gpm)	2-in	3-in	4-in	5-in
10	0.40	0.05		
20	1.44	0.18	0.04	
30	3.05	0.39		
40	5.20	0.66	0.15	
50	7.85	1.00	—	
60	11.01	1.40	0.33	
70	14.65	1.87	0.44	
80	18.76	2.39	0.57	0.19
90	23.33	2.98	0.70	0.23
100	28.36	3.62	0.85	0.28
120		5.07	1.20	0.39
140		6.74	1.59	0.52
160		8.64	2.04	0.67
180		10.74	2.54	0.83
200		13.06	3.08	1.01
220		15.58	3.68	1.21
240		18.30	4.32	1.42
260		21.22	5.01	1.65
280		24.35	5.75	1.89
300			6.54	2.15
320			7.37	2.42
340			8.24	2.71
360			9.16	3.01
380			10.13	3.33
400			11.14	3.66
420			12.19	4.01
440			13.28	4.37
460			14.42	4.75
480			15.61	5.14
500			16.83	5.54
520				5.96
540				6.39
560				6.83
580				7.29
600				7.76

[1] Based on Hazen-Williams formula (C = 130).

Table 11-15.—Reduction coefficients (F) for computing friction loss in pipe with multiple outlets

Number of outlets	F[1] (end)	F[2] (mid)	Number of outlets	F[1] (end)	F[2] (mid)
1	1.00	1.00	8	0.42	0.38
2	0.64	0.52	9	0.41	0.37
3	0.53	0.44	10-11	0.40	0.37
4	0.49	0.41	12-14	0.39	0.37
5	0.46	0.40	15-20	0.38	0.36
6	0.44	0.39	21-35	0.37	0.36
7	0.43	0.38	> 35	0.36	0.36

[1] F(end) is for 1st sprinkler S_l from main (end-riser pipe).
[2] F(mid) is for 1st sprinkler $S_l/2$ from main (mid-riser pipe).

The friction head loss (h_f) in a lateral can be computed by:

$$h_f = J\ F\ L/100 \qquad \textbf{(11-17a)}$$

and the pressure head loss (P_f) is

$$P_f = \frac{J\ F\ L}{231} = h_f/2.31 \qquad \textbf{(11-17b)}$$

Sample calculation 11-7.—Computation of lateral friction loss.

Given:

A 4-in lateral line 1,320 ft long with a 40-ft sprinkler spacing and sprinklers discharging 8 gpm.

Calculation:

The number of sprinklers is N = 1,320/40 = 33

The lateral discharge, Q_t = 33 × 8.00 = 264 gpm

From table 11-15, F = 0.37 and by equation 15 or table 11-14, J = 5.16

By equation 17

$$h_f = J\ F\ L/100 = 5.16 \times 0.37 \times 1{,}320/100 = 24.5 \text{ ft} = 10.6 \text{ psi}$$

Laterals on Level Ground.—The allowable pressure loss due to friction in a lateral line on level ground will be 20 percent of the average design operating pressure for the sprinklers (P_a). Therefore, the allowable head loss gradient (J_a), will be:

$$J_a = \frac{0.20\ P_a \times 2.31}{L/100 \times F} \qquad \textbf{(11-18a)}$$

Using table 11-14 find the flow rate corresponding to the total lateral discharge and, moving along that line to the right, find the pipe-size column that contains a value just equal to or less than J_a. This is the pipe size required. Reverse the procedure to determine the actual pressure loss due to friction (P_f).

To determine the pressure required at the mainline for single pipe size laterals:

$$P_m = P_a + 3/4\ P_f + P_r \qquad \textbf{(11-19a)}$$

and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f + P_r \qquad \textbf{(11-20a)}$$

where

P_m = pressure required at the mainline end (lateral inlet pressure) (psi)
P_f = pressure loss due to pipe friction (psi)
P_r = pressure required to lift water up the riser, riser height/2.31 (psi)

Laterals Laid Uphill.—In figure 11-32, P_f may be equal to 20 percent of P_a minus the pressure required to overcome elevation P_e, which is the difference in elevation divided by 2.31. Therefore:

$$J_a = \frac{(0.20\ P_a - P_e) \times 2.31}{L/100 \times F} \qquad \textbf{(11-18b)}$$

For single pipe size laterals on uniform uphill slopes:

$$P_m = P_a + 3/4\ P_f + 1/2\ P_e + P_r \qquad \textbf{(11-19b)}$$

and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f + 1/2\ P_e + P_r \qquad \textbf{(11-20b)}$$

Sample calculation 11-8 illustrates this procedure.

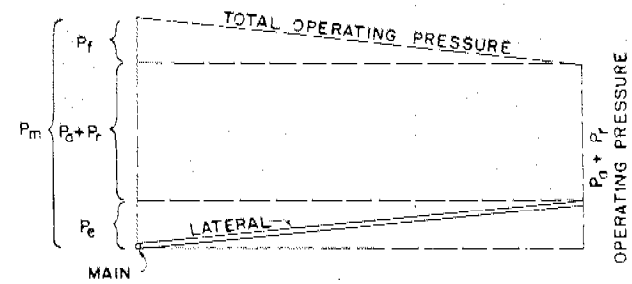


Figure 11-32.—Lateral laid uphill.

Laterals Laid Downhill.—In figure 11-33, the allowable P_f is 0.20 P_a + P_e and for relatively mild slopes:

$$J_a = \frac{(0.20\ P_a + P_e) \times 2.31}{L/100 \times F} \qquad \textbf{(11-18c)}$$

However, on steep slopes where $P_e > 0.4\ P_a$, it is desirable to minimize the pressure variation along the line by reducing pipe sizes. For these conditions, pipe sizes are selected on the basis of friction loss equaling elevation gain, $P_f = P_e$.

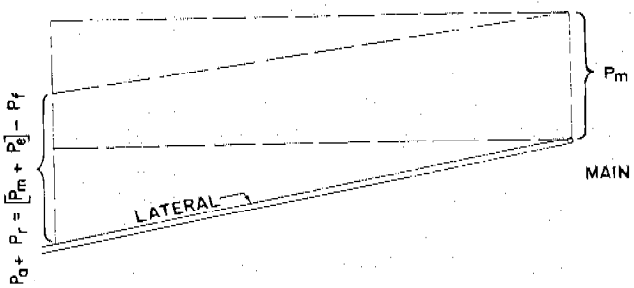


Figure 11-33.—Lateral laid downhill.

For single pipe size laterals on uniform downhill slopes:

$$P_m = P_a + 3/4\ P_f - 1/2\ P_e + P_r \qquad \textbf{(11-19c)}$$

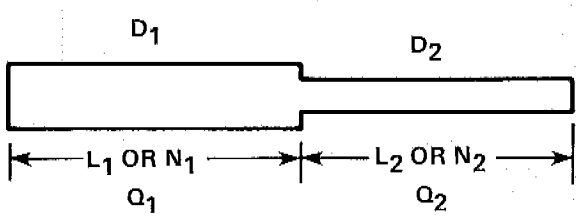
and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f - 1/2\ P_e + P_r \qquad \textbf{(11-20c)}$$

Sample calculation 11-9 illustrates this procedure.

Laterals with Two Pipe Sizes.—Most farmers prefer lateral lines of a single pipe size for convenience. A few want to use two pipe sizes where their use will reduce initial costs. Portable laterals containing more than two pipe sizes should never be considered; however, permanently buried laterals of multiple pipe sizes are practical.

Tables 11-14 and 11-15 can be used to find the nearest uniform pipe size for a lateral line that will result in a friction loss equal to or less than the allowable P_f. The tables may also be used to obtain the lengths of each of two pipe sizes on a lateral line, by using the following procedure:



1. Compute the allowable P_f for the total length of the line as described in the previous sections.
2. Convert this allowable P_f to J_a by using a form of equation 18 appropriate for the slope conditions.
3. With the total lateral line capacity (Q) and the J_a known, use table 11-14 to find the two pipe sizes required.
4. Determine the specific lengths of each of the two pipe sizes required by trial and modification. First estimate lengths L_1 and L_2 and then compute the total pressure loss due to friction for these lengths. The closed end of the multi-outlet line must be considered in all friction-loss calculations using equation 17. Should this loss fall above or below the allowable P_f, choose different values of L_1 and L_2 and repeat the procedure.
5. Assume that pipe diameter D_1 extends for the full length of the lateral line and find the loss for length $L_1 + L_2$ containing $N_1 + N_2$ sprinklers and discharging $Q_1 + Q_2$.
6. Find the loss in length L_2 for pipe diameter (D_1) containing N_2 sprinklers and discharging Q_2.
7. Then find the loss in length (L_2) of pipe diameter D_2 containing N_2 sprinklers and discharging Q_2.
8. Combine the losses as follows:

$$\begin{aligned} P_f &= \text{Step 5} - \text{Step 6} + \text{Step 7} \\ &= P_{f(1+2)}\ (\text{for } D_1) - P_{f(2)}\ (\text{for } D_1) + P_{f(2)}\ (\text{for } D_2) \end{aligned} \qquad \textbf{(11-21)}$$

Sample calculation 11-8 illustrates this procedure.

Sample calculation 11-8.—Laterals laid out uphill—two pipe sizes.

Given:

Lateral consisting of 960 ft of portable aluminum irrigation pipe with 24 sprinklers spaced 40 ft apart, discharging at a rate of 12.5 gpm and operating at 44 psi.

Lateral capacity: Q = 300 gpm

Elevation difference = 9.0 ft (uphill) or P_e = 9.0/2.31 = 3.9 psi

Height of risers for corn: 8.0 ft

Find:

Smallest pipe sizes that will limit pressure loss due to both friction and elevation difference to 20 percent of P_a.

Pressure requirements at the mainline, P_m

Calculation:

Referring to figure 11-32 determine the allowable J_a by equation 18b:

$$J_a = \frac{(0.20 \times 44 - 3.9) \times 2.31}{960/100 \times 0.37} = 3.19$$

Using the lateral capacity of Q = 300 gpm and J_a = 3.19, table 11-14 indicates that some 5-in and some 4-in pipe should be used.

Assuming 480 ft of 5-in and 480 ft of 4-in pipe:

D_1 = 5-in $\qquad$ D_2 = 4-in

$L_1 = 480$ ft $\quad L_2 = 480$ ft
$N_1 = 12 \quad N_2 = 12$
$Q_1 = 150$ gpm $\quad Q_2 = 150$ gpm

Using equation 17b and tables 11-14 and 11-15 and assuming $D_1 = 5$ in for the entire length of the lateral, find the loss in $(L_1 + L_2) = 960$ ft containing $(N_1 + N_2) = 24$ sprinklers and discharging $(Q_1 + Q_2) = 300$ gpm:

$$P_{f(1+2)} \text{ (for } D_1) = \frac{2.15 \times 0.37 \times 960}{231} = 3.31 \text{ psi}$$

Next find the loss in $L_2 = 480$ ft of $D_1 = 5$-in pipe containing

$N_2 = 12$ sprinklers and discharging $Q_2 = 150$ gpm:

$$P_{f(2)} \text{ (for } D_1) = \frac{0.50 \times 0.39 \times 480}{231} = 0.48 \text{ psi}$$

And in a similar manner find the loss in the 4-in pipe:

$$P_{f(2)} \text{ (for } D_2) = \frac{1.81 \times 0.39 \times 480}{231} = 1.47 \text{ psi}$$

The friction loss for the dual pipe size line can now be determined by equation 21:

$$P_f = 3.31 - 0.48 + 1.47 = 4.3 \text{ psi}$$

This value is slightly lower than the allowable $P_f = 0.20\ P_a - P_e = 0.20 \times 44 - 3.9 = 4.9$ psi. Therefore, less 5-in pipe and more 4-in pipe can be used.

By assuming 400 ft of 5-in pipe containing 10 sprinklers and 560 ft of 4-in pipe containing 14 sprinklers, a repetition of the procedure results in:

$$P_f = 3.31 - 0.75 + 2.28 = 4.8 \text{ psi}$$

The pressure requirement at the mainline can now be determined by equation 20b:

$$P_m = 44.0 + (2/3 \times 4.8) + (1/2 \times 3.9) + \frac{8.0}{2.31}$$

$$= 52.6 \text{ psi}$$

Sample calculation 11-9.—Laterals laid downhill.

Given:

Lateral consisting of 960 ft of portable aluminum irrigation pipe with 24 sprinklers spaced 40 ft apart, discharging at a rate of 12.5 gpm, and operating at 44.0 psi

Lateral capacity: $Q = 300$ gpm

Average downhill slope: 3.5 percent and 33.6 ft in total length of line

Height of risers for corn = 8 ft

Owner desires only one pipe size

Find:

Smallest pipe size that will result in an approximate balance between pressure loss due to friction and pressure gain due to elevation decrease.

Pressure requirements at the main line

Calculation:

Assume the allowable P_f to be equal to the pressure gain due to elevation $P_e = \frac{33.6}{2.31} = 14.5$ psi

Convert the pressure gain due to elevation to an allowable head loss gradient (J_a) using equation 18c and letting $P_a = 0$:

$$J_a = \frac{(14.5) \times 2.31}{960/100 \times 0.37} = 9.43$$

Using a lateral capacity of 300 gpm, table 11-14 indicates some 3-in and some 4-in pipe will be required. Since the owner wishes to use only one pipe size, use all 4-in. The pressure loss due to friction resulting from the use of 4-in pipe by equation 17b is:

$$P_f = \frac{0.37 \times 6.54 \times 960}{231} = 10.1 \text{ psi}$$

The percent of pressure variation in the line is:

$$\frac{P_e - P_f}{P_a} = \frac{14.5 - 10.1}{44.0} = 10.0\%$$

If all 3-in pipe were used, the pressure loss due to friction would be 42.5 psi, and the resulting pressure variation would be:

$$\frac{P_f - P_e}{P_a} = \frac{42.5 - 14.5}{44.0} = 64\%$$

This is obviously outside the 20 percent limit. Thus a line consisting of all 3-in pipe should not be used.

Using equation 19c, to compute the pressure required at the mainline for a 4-in lateral:

$$P_m = 44.0 + (3/4 \times 10.1) - (1/2 \times 14.5) + \frac{8.0}{2.31} = 47.8 \text{ psi}$$

Laterals with Flow-Control Devices.—Flow or pressure control devices are used in lateral lines where the topography is too broken or too steep to permit the pressure variation in the line to be controlled within the 20 percent limit by the selection of practical pipe sizes. These devices are either valves placed between the lateral line and the sprinkler head at each sprinkler outlet or special flow control nozzles as described earlier. They are designed to provide equal discharge at all sprinklers. When flow or pressure control devices are used at the base of each sprinkler, the pressure that must be provided at the distal end of the lateral will be P_a plus P_r plus the pressure required to overcome friction loss in the control valves, P_{cv} (fig. 11-34). However, when flexible orifice nozzles are used to maintain constant flow, P_{cv} is effectively zero. Since the valves control the discharge of the sprinklers, the selection of lateral pipe sizes becomes less a problem of maintaining a specified pressure variation between sprinklers and more a problem of economics. The allowable P_f should be that which will result in the lowest annual pumping cost. For most conditions, P_f may be assumed to be about 0.20 P_a or 10 psi.

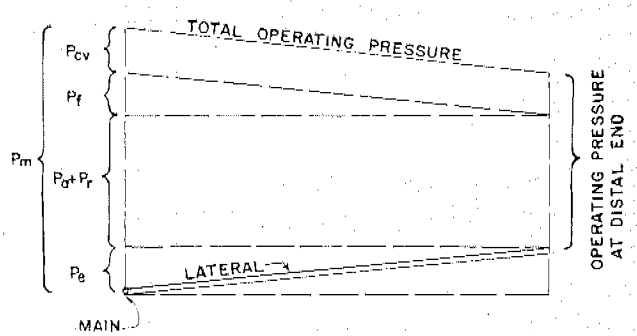


Figure 11-34.—Lateral with flow-control valves.

The pressure requirement at the main line for level fields is:

$$P_m = P_a + P_f + P_r + P_{cv} \qquad \textbf{(11-22a)}$$

for uphill laterals:

$$P_m = P_a + P_f + P_e + P_r + P_{cv} \qquad \textbf{(11-22b)}$$

and for downhill laterals:

$$P_m = P_a + P_f - P_e + P_r + P_{cv} \qquad \textbf{(11-22c)}$$

Valve manufacturers furnish data on the pressure losses for different discharges through their valves (fig. 11-26). Sample calculation 11-10 illustrates the procedure involved in the design of a lateral line containing flow control nozzles.

Sample calculation 11-10.—Design of lateral with flow control nozzles.

Given:

A lateral 1,320 ft long; running up and down slopes on broken topography. The highest point in the line is 33 ft above the lateral inlet from the mainline. The lateral contains 44 sprinklers spaced at S_ℓ = 30 ft with q_a = 5.0 gpm. The first sprinkler is 1/2 S_ℓ from the mainline.

Sprinklers with flexible orifice nozzles designed to discharge about 5 gpm between 40 and 80 psi as shown in figure 11-26 will be used.

The system will have 3-ft risers

The owner desires single pipe size laterals.

Find:

Pipe size and P_m required.

Calculation:

Pressure required to overcome elevation is:

$$P_e = \frac{33}{2.31} = 14.3 \text{ psi}$$

Let the allowable P_f = 10 psi, which is about 20 percent of the pressure that would be required for a standard 5/32-in nozzle discharging 5.0 gpm. The allowable head loss gradient for P_f = 10 psi is:

$$J_a = \frac{10.0 \times 2.31}{1{,}320/100 \times 0.36} = 4.86$$

From table 11-14 for $Q_\ell = 44 \times 5.0 = 220$ gpm it is determined that 4-in pipe will satisfy J_a. Using equation 17b:

$$P_f = \frac{0.36 \times 3.68 \times 1{,}320}{231} = 7.6 \text{ psi}$$

Typically, sprinkler regulating valves have a P_{cv} of between 10 and 15 psi; however, as mentioned earlier for flexible orifice nozzles, $P_{cv} = 0$. Substituting the lowest permissible operating pressure, 40 psi, for P_a in equation 22b:

$$P_m = 40.0 + 7.6 + 14.3 + \frac{3.0}{2.31} + 0 = 63.2 \text{ psi}$$

Hose-Fed Design.—Hose-fed systems for overlapped sprinkler grids and for orchard sprinklers (figs. 11-11 and 11-29D) require special design considerations; however, the design strategies discussed earlier in this section can be used. Each hose may be fitted with from 1 to 10 sprinklers and either periodically pulled to a new set position or left stationary.

If a manifold serves hoses operating with one or two sprinklers in every other tree row, the manifold should be treated as an ordinary sprinkler lateral. The average pressure along the manifold, however, should be the average sprinkler pressure desired (P_a) plus the friction head loss in the hose and hose bib (a hydrant).

If each submain serves only one or two hose lines, with several sprinklers on each (fig. 11-29D), the hose line should be treated as an ordinary sprinkler lateral. Thus, equation 17b is used to find P_f and equation 19 is used to find P_m.

Friction losses in small diameter hoses can be estimated by:

$$J = \frac{h_f}{L/100} = 0.133 \frac{Q^{1.75}}{D^{4.75}} \text{ (for } D < 5 \text{ in)} \qquad \textbf{(11-23a)}$$

This equation is derived by combining the Blasius equation and the Darcy-Weisbach formula for smooth pipes. Equation 23a gives good results for 5-in-diameter and smaller plastic pipe. For larger plastic pipes the Hazen-Williams equation 15 with $C = 150$ can be used; however, slightly more accurate estimates of friction loss can be obtained from:

$$J = \frac{h_f\ 100}{L} = 0.100 \frac{Q^{1.83}}{D^{4.83}} \text{ (for } D > 5 \text{ in)} \qquad \textbf{(11-23b)}$$

Table 11-16 gives friction loss gradients for various sizes of hoses and hose bibs based on equation 23a.

Table 11-16.—Approximate friction loss gradients for plastic hoses and hose bibs[1]

Flow	Friction loss, psi/100 ft [2]			Hydrant loss, psi	
gpm	5/8-in	3/4-in	1-in	3/4-in	1-in
2	1.81	0.76	0.19	0.1	—
4	6.07	2.55	0.65	0.2	0.1
6	12.35	5.19	1.32	0.4	0.2
8	20.43	8.59	2.19	0.8	0.3
10	30.19	12.70	3.24	1.2	0.5
12	41.53	17.47	4.45	1.7	0.7
14		22.88	5.83	2.4	0.9
16		28.90	7.37	3.1	1.2
18		35.52	9.06	3.9	1.5
20			10.89	4.8	1.9
22			12.87	5.8	2.3
24			14.98	6.9	2.7
26			17.24	8.0	3.2
28			19.62	9.2	3.7
30			22.14	10.6	4.3

[1] Nominal hose sizes and also inside diameters.
[2] Friction losses in valves vary widely with different makes of equipment. These values should be used only as a guide in determining the size required.

Perforated-Pipe Laterals.—Since perforated-pipe laterals have equally spaced multiple outlets, the general principles for design of laterals with impact sprinklers also apply to perforated-pipe laterals. Nevertheless, because of their low operating pressure, there are more restrictions on the design of perforated-pipe laterals. Laterals must be laid very nearly on the level if pressure variation along the line is to be kept within acceptable limits. Pressure-control valves cannot be used for this purpose, and only one pipe size should be used.

Perforated pipe is available for only a few rates of application. The most typical rates are 0.75 and 1.0 iph. This limit in application rates materially reduces flexibility in design.

The manufacturers of perforated pipe have simplified the design of laterals by furnishing performance tables for each combination of pipe size and application rate. Knowing the length of the line makes it easy to read the discharge, spread, and operating pressure from the tables. Table 11-17 is an example. The designer should request such tables from the manufacturer when confronted with perforated-pipe-design problems.

Table 11-17.—Typical performance table for perforated pipelines [1]

Inlet pressure	Pipe size = 5-in diameter Application rate = 1.0 iph																			
	Discharge and Spread	Length of line (feet)																		
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950
(psi) 6	gpm	16	32	48	64	80	96	112	127	142	157	172	187	202	217	231	245	259	273	286
	spread	30	30	30	30	30	30	30	29	29	29	29	28	28	28	27	27	26	26	25
7	gpm	17	34	51	68	85	102	119	136	153	170	186	202	218	234	250	265	280	295	309
	spread	33	33	33	33	32	32	32	32	32	32	31	31	31	30	30	29	29	28	27
8	gpm	18	36	54	72	90	108	126	144	162	180	198	215	232	249	266	282	298	314	330
	spread	35	35	35	35	35	35	35	34	34	34	34	33	33	33	33	32	31	30	30
9	gpm	19	38	57	76	95	114	133	152	171	190	209	227	245	263	281	298	315	332	348
	spread	37	37	37	37	37	37	37	37	36	36	36	35	35	35	34	34	33	32	32
10	gpm	20	40	60	80	100	120	140	160	180	200	220	239	258	277	296	314	332	350	367
	spread	39	39	39	39	39	39	38	38	38	38	37	37	37	36	36	35	35	34	33
11	gpm	21	42	63	84	105	126	147	168	189	210	231	251	271	291	311	330	349	368	386
	spread	40	40	40	40	40	40	40	40	40	39	39	39	38	38	37	37	36	36	35
12	gpm	22	44	66	88	110	132	154	176	198	220	241	262	283	304	324	344	364	383	402
	spread	41	41	41	41	41	41	41	41	41	41	40	40	40	39	39	39	38	37	37
13	gpm	23	46	69	92	115	138	161	184	207	230	252	274	296	318	339	360	381	401	421
	spread	43	43	43	43	43	43	42	42	42	42	42	41	41	41	40	40	39	39	38
14	gpm	24	48	72	96	120	144	168	192	216	239	262	285	308	330	352	374	395	416	437
	spread	44	44	44	44	44	44	44	43	43	43	43	42	42	42	41	41	40	40	39
15	gpm	25	50	75	100	125	150	175	199	223	247	271	295	318	341	364	386	408	430	451
	spread	45	45	45	45	45	45	45	45	45	44	44	44	43	43	42	42	41	41	40
16	gpm	26	52	78	104	130	155	180	205	230	255	280	305	324	353	377	400	423	445	467
	spread	46	46	46	46	46	46	46	46	46	46	45	45	44	44	43	43	42	42	41
17	gpm	26	52	78	104	130	156	182	208	234	260	286	311	336	361	385	409	433	456	479
	spread	48	48	48	47	47	47	47	47	47	47	46	46	46	45	45	44	43	43	42
18	gpm	27	54	81	108	135	162	189	216	243	269	295	321	347	372	397	422	446	470	493
	spread	49	49	49	48	48	48	48	48	48	48	47	47	47	46	46	45	44	44	43
[illegible]	gpm	28	56	84	112	140	168	196	224	251	278	305	332	358	384	410	435	460	484	508
	spread	49	49	49	49	49	49	49	49	49	49	48	48	48	47	47	46	45	45	44
20	gpm	29	58	87	116	145	173	201	229	257	285	313	340	367	394	420	446	472	497	522
	spread	50	50	50	50	50	50	50	50	50	49	49	49	48	48	48	47	46	46	45

[1] Furnished by a manufacturer.

To illustrate the use of table 11-17, assume a lateral 750 ft long with S_m = 40 ft applying water at the rate of 1.0 iph. Since this table includes lateral lengths of 750 ft for 5-in pipe and an application rate of 1.0 iph, this size pipe may be used. Find the 750-ft column and follow the column downward until a spread of 42 ft is reached. A spread 2 ft greater than the lateral spacing is customarily used to provide a 1-ft overlap between laterals to prevent dry areas. At a 42-ft spread note that the lateral discharge is 364 gpm. Following a horizontal line to the left, the inlet pressure or pressure required at the mainline, is P_m = 15.0 psi.

Buried Laterals.—The design of buried plastic laterals for permanent systems is essentially the same as for portable aluminum laterals.

The main differences are due to the difference in pipe friction and the fact that up to 4 different pipe sizes are often used. To determine friction loss use equation 23 to compute the P_f of a multisized lateral either following a procedure similar to that outlined in this section under subtopic *Laterals for Two Pipe Sizes* or the graphical procedures developed in Chapter 7, *Trickle Irrigation*.

Mainline Design

Mainlines for sprinkler systems vary from short portable feeder lines to intricate networks of buried mains and submains for large systems. The principal function of mainlines and submains is to convey the quantities of water required to all parts of the design area at the pressure required to operate all laterals under maximum flow conditions. The principal design problem is the selection of pipe sizes that will accomplish this function economically. For the purposes here, the line running from the water source to the design area, usually called the supply line, will be treated as part of the mainline.

The design of mainlines or submains requires an analysis of the entire system to determine maximum requirements for capacity and pressure.

Friction Tables.—The Hazen-Williams equation is the most commonly used formula for computing friction loss in aluminum mainline pipes. Table 11-18 gives friction loss J values in ft/100 ft for portable aluminum irrigation pipe with typical mainline coupler losses assuming 30-ft pipe lengths.

Tables 11-19a and 11-19b give J values for SDR 41 PVC, IPS, and PIP (Class 100 psi) thermoplastic pipe used in typical sprinkle irrigation system mainlines. The values in these tables were computed using equation 23 which gives slightly more accurate estimates than the Hazen-Williams equation with C = 150 for smooth plastic pipe.

Table 11-18.—Friction loss J values in ft/100 ft of portable aluminum mainline pipe with couplers connecting 30-foot lengths [1]

Flow rate (gpm)	5-in [2] (0.050) (4.900)	6-in (0.058) (5.884)	8-in (0.072) (7.856)	10-in (0.091) (9.818)	12-in (0.091) (11.818)
100	0.28	0.12			
150	0.60	0.24			
200	1.01	0.42	0.10		
250	1.53	0.63	0.15		
300	2.15	0.88	0.22		
350	2.86	1.17	0.29		
400	3.66	1.50	0.37	0.12	
450	4.56	1.87	0.46	0.15	
500	5.54	2.27	0.56	0.19	
550	6.61	2.71	0.66	0.22	
600	7.76	3.18	0.78	0.26	
650	9.00	3.69	0.90	0.31	
700		4.24	1.04	0.35	0.14
750		4.81	1.18	0.40	0.16
800		5.42	1.33	0.45	0.18
850		6.07	1.49	0.50	0.20
900			1.65	0.56	0.23
950			1.83	0.62	0.25
1000			2.01	0.68	0.27
1100			2.39	0.81	0.33
1200			3.81	0.95	0.39
1300			3.26	1.10	0.45
1400			3.74	1.26	0.51
1500			4.25	1.44	0.58
1600			4.79	1.62	0.66
1800			5.96	2.01	0.82
2000			7.25	2.45	0.99
2200			8.64	2.92	1.18
2400				3.43	1.39
2600				3.98	1.61
2800				4.56	1.85
3000				5.18	2.10
3500					2.80
4000					3.58

[1]Based on Hazen-Williams equation with C = 130; 20-ft pipe increases by 7% and 40-ft pipe decreases by 3%.
[2]Outside diameter; wall thickness and inside diameter in parentheses.

Table 11-20 gives J values for welded steel pipe. The table is based on Skobey's formula, which is generally used for estimating friction in steel pipe

$$J = \frac{h_f\ 100}{L} = \frac{K_f}{10}\ \frac{V^{1.9}}{(D/12)^{1.1}} \qquad \textbf{(11-24)}$$

Table 11-19a.—Friction-loss J values in ft/100 ft of SDR 41, IPS, PVC (Class 100 psi) thermoplastic pipe used for sprinkle irrigation mainlines (based on equation 23a)

Flow rate (gpm)	4-in[1] (4.280)	6-in (6.301)	8-in (8.205)	10-in (10.226)	12-in (12.128)
100	0.43				
150	0.86				
200	1.42				
250	2.09				
300	2.88	0.47			
350	3.77	0.62			
400	4.77	0.80			
450	5.86	0.99			
500		1.20	0.33		
550		1.42	0.40		
600		1.67	0.47		
650		1.93	0.54		
700		2.22	0.62	0.21	
750		2.51	0.70	0.24	
800		2.83	0.79	0.27	
850		3.16	0.88	0.30	
900		3.51	0.98	0.34	
1000		4.25	1.19	0.41	0.18
1100		5.07	1.41	0.49	0.21
1200		5.94	1.66	0.57	0.25
1300			1.92	0.66	0.29
1400			2.20	0.76	0.33
1500			2.50	0.86	0.38
1600			2.81	0.97	0.43
1700			3.14	1.08	0.48
1800			3.48	1.20	0.53
2000			4.23	1.46	0.64
2200			5.03	1.74	0.76
2400			5.90	2.04	0.89
2600				2.36	1.03
2800				2.70	1.18
3000				3.05	1.34
3200				3.45	1.51
3600				4.28	1.88
4000				5.19	2.28

[1] Nominal pipe diameter; inside diameter in parentheses.

Table 11-19b.—Friction loss J values in ft/100 ft of SDR 41, PIP, PVC (Class 100) thermoplastic pipe used for spinkle irrigation mainlines (based on equation 23b)

Flow rate (gpm)	6-in[1] (5.840)	8-in (7.762)	10-in (9.702)	12-in (11.642)	15-in (14.554)
300	0.68				
350	0.90				
400	1.15				
450	1.42				
500	1.73	0.44			
550	2.06	0.52			
600	2.41	0.61			
650	2.79	0.71			
700	3.20	0.81	0.28		
800	4.08	1.03	0.35		
900	5.06	1.28	0.44		
1000	6.14	1.55	0.53		
1100		1.85	0.63	0.26	
1200		2.17	0.74	0.31	
1300		2.51	0.86	0.35	
1400		2.88	0.98	0.41	
1600		3.67	1.25	0.52	0.18
1800		4.56	1.55	0.64	0.22
2000		5.52	1.88	0.78	0.27
2200		6.58	2.24	0.93	0.32
2400			2.63	1.09	0.37
2600			3.04	1.26	0.43
2800			3.48	1.44	0.49
3000			3.95	1.64	0.56
3500				2.17	0.74
4000				2.77	0.94
4500				3.44	1.17
5000				4.17	1.42
5500					1.69
6000					1.98
6500					2.29
7000					2.63

[1] Nominal pipe diameter; inside diameter in parentheses.

where

K_f = Skobey's friction coefficient that is normally taken as 0.36 for 15-year-old welded steel.

V = flow velocity (ft/s)

Other types of pipe material such as asbestos-cement are available and practical for sprinkle system mainlines. As a general rule, each manufacturer of pipe material has friction loss tables available for the particular class of pipe offered. It is impractical to include all such tables in this handbook, and the designer should obtain from the manufacturers appropriate friction-loss tables for pipe materials other than those included here.

Most friction loss tables furnished by manufacturers are for new pipe unless otherwise stated. The designer should allow for aging of the pipe by adding a percentage of the loss consistent with the type of material and the average life of the pipe.

General Design Procedure.—The loss in pressure caused by friction is the primary consideration in the design of any pipe system. The basic problems vary depending on the source of pressure.

When the pressure required for sprinkle system operation is supplied by pumping, the problem is

Table 11-20.—Friction loss in ft/100 ft (J), in mainlines of 8-to-12 year old welded steel pipe (based on Skobey's formula with $K_f = 0.36$)

Flow (gpm)	4-in [1]			5-in [1]		6-in [1]		7-in [1]		8-in [1]		10-in [1]	
	16-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage
40	0.150	0.155	0.169	0.048	0.052								
50	.218	.227	.246	.074	.080								
60	.300	.312	.339	.106	.113								
70	.393	.411	.444	.142	.151								
80	.558	.579	.628	.182	.193	0.074	0.079						
90	.677	.709	.768	.228	.242	.091	.096						
100	.810	.848	.920	.279	.296	.109	.115	0.052	0.054				
125	1.28	1.34	1.45	.425	.452	.172	.181	.079	.082				
150	1.76	1.83	1.99	.602	.640	.235	.249	.111	.116				
175	2.42	2.52	2.73	.807	.857	.323	.341	.148	.155	0.075	0.080		
200	3.04	3.17	3.44	1.04	1.10	.407	.429	.191	.200	.096	.100		
250	4.79	5.01	5.43	1.59	1.69	.643	.678	.292	.306	.152	.159	0.050	0.052
300	6.74	7.04	7.63	2.25	2.39	.903	.953	.414	.432	.215	.223	.070	.072
350	8.99	9.41	10.2	3.01	3.23	1.21	1.27	.555	.579	.287	.297	.095	.097
400	11.5	12.1	13.1	3.88	4.12	1.55	1.63	.714	.746	.369	.381	.120	.124
450	14.4	15.3	16.3	4.85	5.16	1.94	2.04	.894	.934	.458	.476	.150	.155
500	17.6	18.6	19.9	5.93	6.30	2.36	2.49	1.09	1.14	.559	.580	.183	.189
600				8.38	8.91	3.39	3.57	1.54	1.61	.801	.834	.263	.271
700				11.2	11.9	4.51	4.76	2.07	2.16	1.07	1.11	.352	.361
800				14.5	15.4	5.79	6.10	2.67	2.79	1.37	1.42	.450	.464
900						7.28	7.68	3.34	3.48	1.73	1.79	.573	.584
1000						8.90	9.38	4.08	4.26	2.11	2.18	.694	.712
1200						12.5	13.2	5.76	6.02	3.04	3.07	.977	1.00
1400								7.73	8.07	3.98	4.14	1.30	1.35
1600								9.96	10.4	5.13	5.33	1.68	1.74
1800										6.43	6.66	2.12	2.17
2000										7.86	8.18	2.62	2.65
2500										12.0	12.5	3.97	4.05
3000												5.52	5.74

[1] Outside diameters.

one of selecting mainline pipe sizes and pipe materials that will result in a reasonable balance between annual pumping costs and the capitalized cost of the pipe. The ultimate objective is to arrive at a design that results in the lowest annual water application cost.

Normal procedure is to assume, within a reasonable range, several values of allowable head loss due to friction in mainlines and submains and to compute the pipe size or sizes for each assumed value. The pipe sizes thus obtained are then checked for power economy and the most economical sizes are selected. Experience shows that head loss values assumed over a range of 10 to 40 ft, as in the first step in this procedure, will prove adequate.

If gravity pressure (pressure gained by elevation differences) is used, one of two problems may arise. When elevation differences are scarcely enough to provide adequate pressure for operation of the system, the problem becomes one of conservation of energy demanding larger than normal pipe sizes to reduce friction losses and to avoid booster pumping where possible. When elevation differences considerably exceed those required to provide normal operating pressure, the problem becomes one of reducing pressure gains, thus requiring small pipe sizes to increase friction losses. On very steep slopes, this procedure is required to protect the mainline and other equipment in the system.

In addition to pressure loss considerations, the velocity of flow in mainlines should be restricted to eliminate excessive water hammer. This is particularly important in PVC and cement-asbestos pipelines. NI PVC pipe design, mainline velocities should be limited to 5.0 ft/s. With SDR-41 PVC pipe, the surge pressure is approximately equal to 12.4 psi for each 1.0 ft/s velocity change.

Design with Single Lateral.—When only one lateral is moved along one or both sides of a mainline, selecting the mainline pipe size is relatively simple. The pipe size may be selected directly from tables or from appropriate formulas that will result in a friction loss not exceeding the allowable limit when the lateral is operating from the distal end of the mainline.

If two laterals are being moved along a mainline but are not rotated in split-line operation, the problem is the same as if a single lateral were being used. The size of pipe selected will be that which will result in a friction loss within allowable limits when both laterals are discharging from the distal end of the main.

Design with Split-Line Layout.—The split-line layout consists of two or more laterals rotated around the mainline or submains. Its purpose is twofold: (1) to equalize the load at the pump regardless of lateral position, and (2) to minimize the haulback of lateral pipe to the beginning point.

Figure 11-35 uses a split-line layout to illustrate the problem of mainline design. In this layout, one lateral is moved up one side of the mainline while the other lateral is moved down the other side. It is apparent that at times the full quantity of water (Q) will have to be carried from A to B. At such times there will be no flow beyond B. From B to C, the flow will never exceed Q/2, and when one lateral is operating at C, requiring a flow of Q/2 at that point, the other lateral will be at A, thus the flow for the entire length of main will be Q/2.

For any given total head at the pump, the smallest pipe sizes will be the ones that result in equal values for H_{f1} and $H_{f2}+E_2$. Note that the elevation difference between B and C (E_2) in figure 11-35 is positive for uphill and negative for downhill lines. After pipe sizes have been computed for any reasonable value for head loss, adjustments can be made to balance annual pumping costs and capitalized pipe costs. For mains fed from pressure systems, the available head is fixed, and the smallest pipe sizes that will deliver the required flow to the laterals should be used.

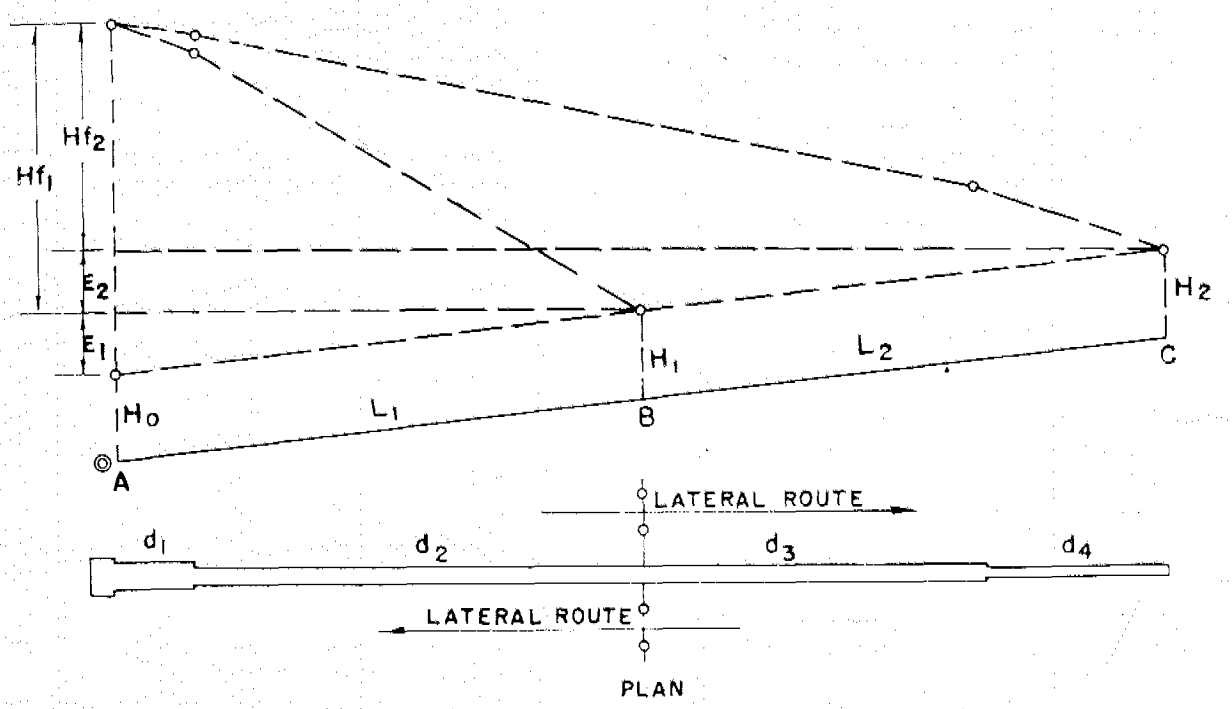
A simple procedure to follow in determining minimum pipe sizes for a given limit of head loss follows:

1. Find the pipe size from the appropriate table that will carry the flow in the first length of main (L_1) with a friction loss equal to or just larger than allowed.
2. If the friction loss for length of pipe L_1 using the selected pipe size exceeds the H_{f1} limit, find the friction loss in the next larger size pipe.
3. Determine the proportionate lengths for L_1 for the two pipe sizes as follows:

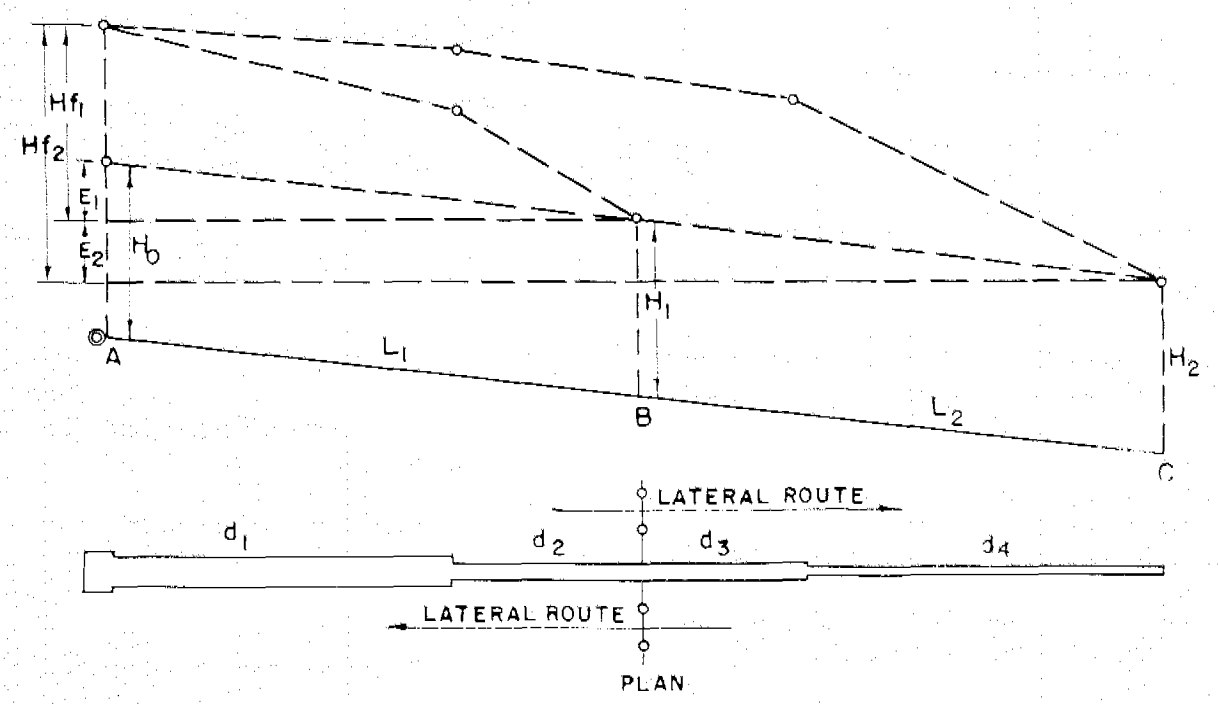
$$H_{f1} = XJ_2 + (L_1 - X)J_1 \qquad \textbf{(11-24a)}$$

where

H_{f1} = limit of friction loss in length of pipe (ft)



A_MAIN LINE RUNNING UPHILL



B_MAIN LINE RUNNING DOWNHILL

Figure 11-35.—Design of mainline with twin laterals, split-line operation.

X = length of smaller pipe (ft/100 ft)
J_2 = friction loss gradient in smaller pipe (ft/100 ft)
$(L_1 - X)$ = length of larger pipe (ft/100 ft)
J_1 = friction loss gradient in larger pipe (ft/100 ft)

Solving equation 24a for X gives:

$$X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1} \qquad \textbf{(11-24b)}$$

4. Determine the pipe size requirements for length L_2 by:

$$H_{f2} = J_1 L_{d1} + J_2 L_{d2} + J_3 (L_2 - Y) + J_4 Y \qquad \textbf{(11-25a)}$$

where

H_{f2} = limit of friction loss in entire mainline (ft)
L_{d1} = length of pipe of diameter D_1 (ft/100 ft)
L_{d2} = length of pipe of diameter D_2 (ft/100 ft)
$L_2 - Y$ = length of pipe diameter D_3 (ft/100 ft)
Y = length of pipe of diameter D_4 (ft/100 ft)
J_1, J_2, J_3, and J_4 – friction loss gradients in respective pipe diameters, D_1, D_2, D_3, and D_4 (ft/100 ft)

Solving equation 25a for Y gives:

$$Y = \frac{H_{f2} - J_1 L_{d1} - J_2 L_{d2} - J_3 L_2}{J_4 - J_3} \qquad \textbf{(11-25b)}$$

Sample calculation 11-11 illustrates the problem of mainline design when two laterals are operated in a split-line manner.

Sample calculation 11-11.—Uphill mainline with twin lateral split-line operation.

Given:
Refer to figure 11-35A.
Q, capacity of system: 500 gpm
Length of supply line (water source to design area): 440 ft aluminum pipe (30-ft sections)
L, length of mainline (within design area): 1,200 ft aluminum pipe (30-ft sections)
L_1 = 600 ft L_2 = 600 ft
$H_0 = H_1 = H_2$ = 125 ft (head required to operate laterals)
$E_1 = E_2$ = 7.0 ft (elevation difference in mainline assuming uniform slope).
Total allowable head loss due to friction: 33.0 ft.

Find:
Smallest pipe sizes for both supply line and mainline that will limit friction head to 33.0 ft.

Calculation:
Assume 6-in diameter of supply line
From table 11-18, friction loss in 6-in pipe for 500 gallons per minute = 2.27 ft per 100 ft
Friction loss in 440-ft supply line = 4.4 × 2.27 = 10.0 ft

Then H_{f2} = 33.0 − 10.0 = 23.0 ft and H_{f1} = $H_{f2} + E_2$ = 23.0 + 7.0 = 30.0 ft

H_{f1} is greater than H_{f2} by E_2 because when both laterals are operating at position B, the pump is not operating against static head E_2, thus advantage can be taken of this by increasing the allowable friction loss in Section A-B.

When both laterals are operating from position B, Q = 500 gpm and L_1 = 600 ft

Average loss through length $L_1 = H_{f1} \div L_1/100$

$$= \frac{30.0}{6} = 5.0 \text{ ft/100 ft}$$

From table 11-18, 5- and 6-in pipe are indicated for D_2, friction loss in 5-in pipe, J_2 = 5.54 ft/100 ft and for D_1, friction loss in 6-in pipe, J_1 = 2.27 ft/100 ft. Let X = length of D_2, then 600 − X = length of D_1 and by equation 24b:

$$X = \frac{30.0 - (2.27 \times 600/100)}{5.54 - 2.27} \times 100$$
$$= 500 \text{ ft}$$

Use 500 ft of 5-in pipe and 600 − 500 = 100 ft of 6-in pipe. When one lateral is operating from position A and the other is operating from position C, Q = 250 gpm.

The average loss through length $L_2 = H_{f2} \div$

$$L_2/100 = \frac{23.00}{6} = 3.83 \text{ ft/100 ft. From table}$$

11-14, 4- and 5-in pipe are indicated.

For D_4, friction loss in 4-in pipe, J_4 = 4.66 ft/100

ft; for D_3 and D_2, friction loss in 5-in pipe, $J_3 = J_2 = 1.53$ ft/100 ft; and for D_1, friction loss in 6-in pipe, $J_1 = 0.63$ ft/100 ft.

Let Y = length of D_4, then 600 − Y = length of D_3 pipe, and by equation 25b:

$$Y = \frac{23.0 - (0.63 \times 100/100) - (1.53 \times 500/100) - (1.53 \times 600/100)}{(4.66 - 1.53)} \times 100 = 177 \text{ ft}$$

Use 180 ft of 4-in pipe, 600 − 180 = 420 ft of 5-in pipe in L_2. Thus the mainline will consist of:

100 ft of 6-in pipe
500 + 420 = 920 ft of 5-in pipe
180 ft of 4-in pipe

Similar calculations should be made for different assumed values of allowable friction head loss (H_f) to determine the most economical pipe sizes.

Design with Multiple Laterals in Rotation.—If more than two laterals are operated and the flow in the mainline is split, with part of the first lateral taken out and the rest continuing in the mainline to serve other laterals, the design problem becomes more complex (fig. 11-36).

No simple mathematical formulas can be used to determine the minimum pipe sizes. Approximations can be made, however, by inspection and by trial and error calculations.

As a starting point, assume that the total allowable friction loss should be distributed in a straight line for flows reaching the far end of the main. The allowable loss for each reach of main will then be proportional to the length of the reach.

Using the method and formulas developed for the split-line design, minimum pipe sizes can be determined to fit the allowable head loss values for each reach of mainline. The resulting head loss will approximate a straight line loss and will coincide with the straight line at each control point as shown on the profile in figure 11-36.

The mainline thus designed will satisfy the requirements for operation with one lateral at the far end of the mainline. It must then be checked to see that it will satisfy the requirements for operation with laterals in other positions on the line. If the design does not satisfy the requirements for all operating conditions, it will have to be adjusted.

After completing a design satisfactory for a given total allowable friction head loss, similar designs for other values of head loss can be used in balancing pipe and power costs.

Design of Main and Submain Layout.—If several submains are used to operate laterals, the design of the mainline system is a series of individual problems where the maximum operating head requirements for each submain must be computed. The solution for minimum pipe sizes consistent with allowable head loss is similar to the mainline-design problem in sample calculation 11-11. Figure 11-37 illustrates how to determine the maximum head requirements at the pump on the basis of the maximum requirements for submain 2. In this case, if the submain serves a small part of the total area, a booster pump might be used, thus reducing the requirements at the main pump as shown by the alternate line on figure 11-37.

Life Cycle Costs.—The most economical size or combination of sizes of pipe in a mainline or submain is that which will result in a reasonable balance between the annual cost of owning the pipe and the annual pumping cost. The balance depends primarily on two factors: (1) the seasonal hours of operation, and (2) the cost of the power used.

For example, in humid areas a system may be operated for 500 hours per season, or less, and power rates may be comparatively low. Then the annual cost of pumping against friction head is low and a reduction in mainline pipe sizes would ordinarily be justifiable. On the other hand, in an area where full season operation is required and power costs are high, pumping against friction head is much more costly. An increase in mainline pipe sizes is often required to achieve balance.

To find the most economical life-cycle costs of a system, the designer must find the minimum sum of the fixed plus operating costs. To visualize this, think of selecting the diameter of a water supply line. If a very small pipe is used the fixed cost will be low, but the operating cost of overcoming friction losses in the pipe will be large. As the pipe diameter is increased the fixed costs will also increase, but the power costs will decrease. The optimum pipe size is the one for which the fixed plus power costs are least.

The life-cycle cost analysis can be made on a present worth or on an annual basis. In either case the interest rate (i) the expected life of the item (n) and

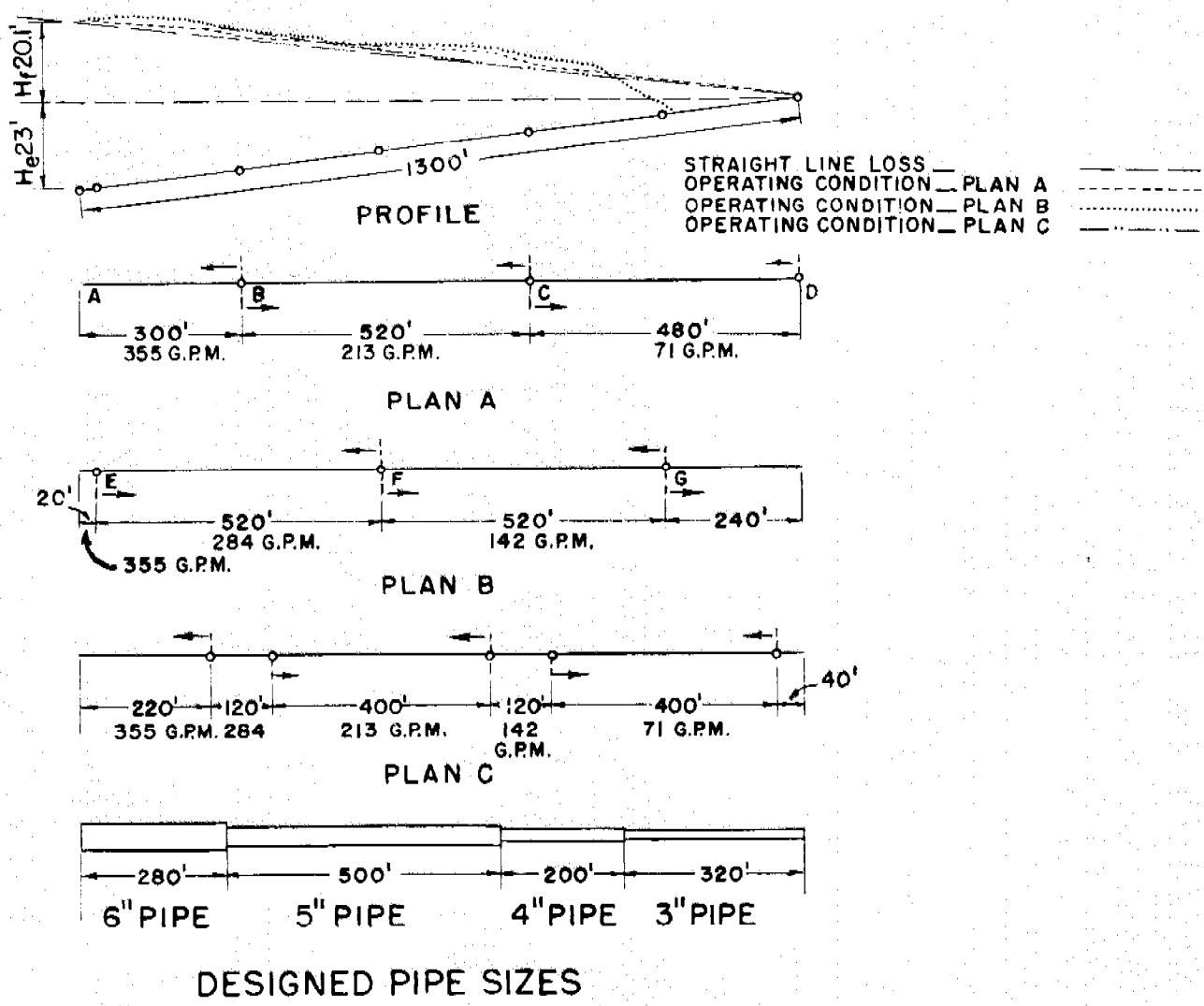


Figure 11-36.—Design of an uphill mainline with five 71 gpm laterals, split-line operation assuming the allowable friction head loss is 20.1 ft and the elevation difference is 23 ft.

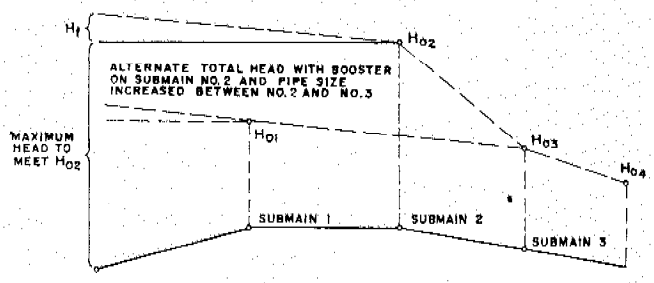


Figure 11-37.—Maximum operating conditions with submains.

an estimate of the expected annual rate of escalation in energy costs (e) must be considered. The present worth of the escalating energy factor (PW(e)) and the equivalent annual cost of the escalating energy factor (EAE(e)) can be computed by the following equations for $e \neq i$:

$$PW(e) = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right] \quad (11\text{-}26)$$

and

$$EAE(e) = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\frac{i}{(1+i)^n - 1}\right] \quad (11\text{-}27)$$

The standard capital recovery factor is computed by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (11\text{–}28)$$

where

e = decimal equivalent annual rate of energy escalation
i = time value of unsecured money to the developer or the decimal equivalent annual interest rate
n = number of years in the life cycle
PW(e) = present worth factor of escalating energy costs, taking into account the time value of money over the life cycle.
EAE(e) = equivalent annual cost factor of escalating energy, taking into account the time value of money over the life cycle.
CRF = uniform series annual payment (capital recovery factor), which takes into account the time value of money and depreciation over the life cycle.

When considering life-cycle costs, the time value of unsecured money to the developer should be used as the appropriate interest rate (i). This is normally higher than bank interest rates because of the higher risks involved. Returns from unsecured agricultural developments should be about 10 percent higher than the interest rates on high grade, tax-free, long-term securities unless some special tax benefits are involved.

Table 11–21 gives the necessary factors for either a present worth or an annual life-cycle cost analysis. The table gives factors for 9 percent and 13.5 percent annual escalation in energy costs for 10 to 25 percent interest rates and for life cycles of 7 to 40 years. The value PW(0%) is the present worth factor of nonescalating energy, taking into account the time value of money over the life cycle.

The expected life of different mainline pipe materials is:

Portable aluminum	10–20 yr
Coated welded steel	10–20 yr
PVC plastic	20–40 yr
Cement-asbestos	20–40 yr

However, because of obsolescence, life cycles of n = 20 or less are frequently used for all pipes.

The number of brake horsepower (BHP) hours per unit of fuel that can be expected from efficient power units is:

Diesel	15.0 BPH hrs/U.S. gallon
Gasoline (water cooled)	10.5 BPH hrs/U.S. gallon
Tractor fuel	8.5 BPH hrs/U.S. gallon
Butane-propane	9.5 BPH hrs/U.S. gallon
Natural gas	8.5 BPH hrs/100 cubic feet
Electric	1.20 BPH hrs/kwh @ meter

The factors presented in Table 11–21 can be used with the present annual power costs (U) and the cost of the irrigation system (M) to estimate the following:

1. The present worth of energy escalating at 9 percent per year is equal to U × PW(9%).
2. The equivalent annual cost (U′) of energy escalating at 9 percent per year is U′ = U × EAE (9%).
3. The annual fixed cost of the irrigation system is M × CRF.
4. The present worth of nonescalating energy is U × PW(0%).
5. In addition, it is obvious that the annual cost of nonescalating energy is equal to U.
6. The present worth of the irrigation system is equal to M.

Although the selection of economical pipe sizes is an important engineering decision, it is often given insufficient attention, especially in relatively simple irrigation systems. Many designers use an arbitrary flow velocity or a unit friction loss to size pipe because they consider the methods for selecting economic pipe size too time consuming, limited, or complex. The economic pipeline selection chart presented here was developed to help remedy this situation. The chart can be constructed for a given set of economic parameters and used to select directly the most economical pipe sizes for nonlooping systems having a single pump station. The chart approach to economic design is particularly useful when technicians are employed to design a number of simple systems having the same economic parameters.

Economic Pipe Selection Chart.—The following example demonstrates how the chart is constructed:

Step 1.—The necessary economic data must be obtained.

a. For a 20 percent time value of money and expected life cycle of aluminum mainline pipe of 15 years from table 11–21, CRF = 0.214 and EAE(9%) = 1.485.

Table 11-21.—Present worth and annual economic factors for assumed escalation in energy costs of 9 percent and 13.5 percent and various interest rates and life cycles

Factor	Interest (i)	Life cycle (n) years					
	%	7	10	15	20	30	40
PW(13.5%)	10	7.004	10.509	17.135	24.884	44.547	71.442
EAE(13.5%)		1.439	1.710	2.253	2.923	4.726	7.306
PW(9%)		6.193	8.728	12.802	16.694	23.965	30.601
EAE(9%)		1.272	1.420	1.683	1.961	2.542	3.129
CRF		0.205	0.163	0.132	0.118	0.106	0.102
PW(0%)		4.868	6.145	7.606	8.514	9.427	9.779
PW(13.5%)	15	5.854	8.203	11.917	15.396	21.704	27.236
EAE(13.5%)		1.407	1.634	2.038	2.460	3.306	4.101
PW(9%)		5.213	6.914	9.206	10.960	13.327	14.712
EAE(9%)		1.253	1.378	1.574	1.751	2.030	2.215
CRF		0.240	0.199	0.171	0.160	0.152	0.151
PW(0%)		4.160	5.019	5.848	6.259	6.566	6.642
PW(13.5%)	20	4.967	6.569	8.712	10.334	12.490	13.726
EAE(13.5%)		1.378	1.567	1.863	2.122	2.509	2.747
PW(9%)		4.453	5.615	6.942	7.762	8.583	8.897
EAE(9%)		1.235	1.339	1.485	1.594	1.724	1.781
CRF		0.277	0.239	0.214	0.205	0.201	0.200
PW(0%)		3.605	4.193	4.676	4.870	4.979	4.997
PW(13.5%)	25	4.271	5.383	6.651	7.434	8.215	8.513
EAE(13.5%)		1.351	1.508	1.723	1.880	2.056	2.128
PW(9%)		3.854	4.661	5.449	5.846	6.147	6.224
EAE(9%)		1.219	1.306	1.412	1.479	1.539	1.556
CRF		0.316	0.280	0.259	0.253	0.250	0.250
PW(0%)		3.161	3.571	3.859	3.954	3.995	4.000

b.

Nominal diameter	Price/100 ft	Annual fixed cost/100 ft (0.214 × price/100 ft)
5-in	\$150	\$32.10
6-in	\$200	\$42.80
8-in	\$250	\$53.50
10-in	\$300	\$64.20
12-in	\$350	\$74.90

c. Diesel fuel @ \$1.05/gal gives \$0.07/BHP-hr

d. Estimated hours of operation/year are 1,000

e. Hazen-Williams resistance coefficient for portable aluminum mainline pipe is C = 130.

Step 2.—Determine the yearly fixed cost difference between adjacent pipe sizes and enter this in table 11-22.

Step 3.—Determine the equivalent annual cost per water horsepower (WHP) hour of energy escalating at 9 percent per year as follows, assuming a 75 percent pump efficiency:

a. The present annual cost of energy is:

$$U = \frac{1000 \text{ hr/yr} \times \$0.07/\text{BHP-hr}}{0.75 \text{ WHP/BHP}} \quad (11\text{-}29)$$

$$U = \$93.33/\text{WHP-year}$$

b. The equivalent annual cost of energy at EAE (9%) = 1.485 is:

$$U' = 1.485 \times \$93.33/\text{WHP-year}$$
$$= \$138.60/\text{WHP-year}$$

Table 11-22.—Sample data and procedure for locating economic pipe size regions on selection chart, C = 130, CRF = 0.214, U′ = \$138.60/WHP-year and Q = 1,000 gpm

Step	Item	Adjacent pipe sizes Nominal diameters (inches)			
		5–6	6–8	8–10	10–12
2	Yearly fixed-cost difference · \$/100	10.70	10.70	10.70	10.70
4	Water horse power (WHP)	0.077	0.077	0.077	0.077
5	ΔJ − ft/100 ft	0.31	0.31	0.31	0.31
6	Q − gpm	140	200	450	850

Step 4.—The WHP savings needed to offset the annual fixed cost difference between adjacent pipe sizes are equal to the fixed cost difference divided by U'. The required values are presented in table 11-22 and an example calculation for 6-8 in pipe is:

$$\text{WHP (6-8)} = \frac{\$10.70/100 \text{ ft-yr}}{\$138.60/\text{WHP-yr}} \qquad (11\text{-}30)$$

$$= 0.077 \text{ WHP/100 ft}$$

Step 5.—The head loss difference (ΔJ) between adjacent pipe sizes needed to obtain the above WHP is presented in table 11-22 and an example calculation for an assumed system flow rate, Q = 1,000 gpm is:

$$\Delta J(6\text{-}8) = \frac{0.077 \text{ WHP/100 ft} \times 3{,}960}{1{,}000 \text{ gpm}}$$

$$= 0.31 \text{ ft/100 ft}$$

Step 6.—The flow rates (q) that would produce the required ΔJ between adjacent pipe sizes are shown in table 11-22. These flow rates can be determined by trial and error using J values from pipe friction loss calculators or tables. For example, to get J(8-10) = 0.31 ft/100 ft at q = 450 gpm from table 11-18:

$$J(8) = 0.46 \text{ ft/100 ft}$$
$$J(10) = 0.15 \text{ ft/100 ft}$$
$$\Delta J(8\text{-}10) = 0.31 \text{ ft/100 ft}$$

To obtain ΔJ values directly, construct a log-log graph of flow versus head loss differences between adjacent pipe sizes.

Step 7.—Plot the points representing the system flow used in step 5 (Q = 1,000 gpm) at the pipe flow rates determined in step 6, on log-log graph paper as in figure 11-38 (see the open circles).

Step 8.—Draw lines—with a slope equal to the exponent for Q or V in the pipe friction equation used—through each of the points plotted in step 7. In this case use a slope of −1.85. These lines represent the set of pipe flow rates (q) that gives the same fixed plus operating cost with adjacent sizes of pipe for different system flow rates (Q). Each pair of lines defines the region in which the size common to both lines is the most economical pipe to use.

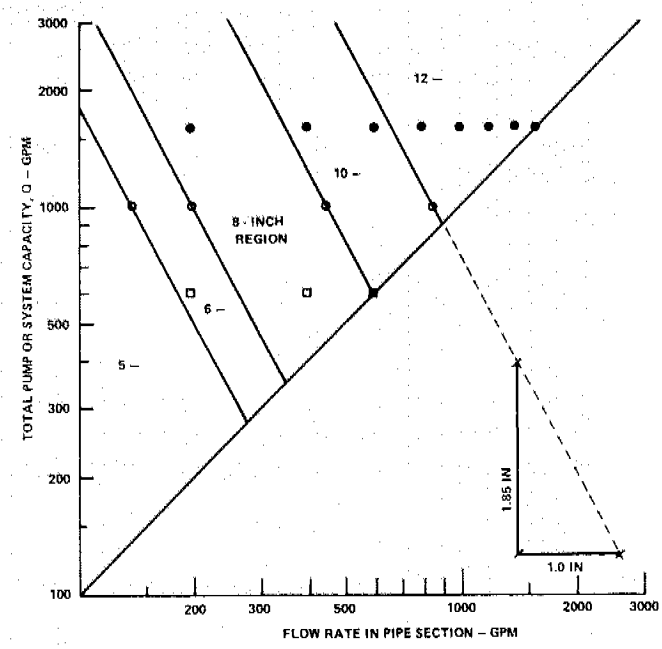


Figure 11-38.—Economic pipe selection chart for portable aluminum pipe with C=130, CRF=0.214, and U' =$138.60/WHP-year.

Figure 11-38 shows the complete economic pipe size selection chart. The circles on the 2 × 2 cycle log-log graph paper at a system flow rate Q = 1,000 gpm represent the pipeline flow rates (q) found in step 6 and presented in the last line of table 11-22.

Changing any of the economic factors will shift the lines in the chart shown in figure 11-38. Developing a new chart for a new set of economic factors is simple when the spacing between lines remains constant, such as for a new U' (CRF) or when the pipe prices all change proportionally. Construction of steps 1 through 6 needs to be repeated for only one pair of adjacent pipe sizes at a single Q. This Q vs. q point locates the new position for the lines in question and all other lines can be shifted an equal distance and drawn parallel to their original positions.

Design of Economical Mainline.—The negative sloping lines on figure 11-38 represent all the possible Q vs. q values for each of the adjacent pairs of pipe sizes that will give the same sum of fixed plus operational costs. The zone between adjacent lines defines the region of Q vs. q values when the pipe size that is common to both lines is the most economical selection. The chart is universally applicable for the most economical pipe size selections in

any sized series system for the economic boundary conditions assumed. Two example systems are given to demonstrate the use of the chart:

Sample calculation 11-12. Use of economic pipe selection chart.

Given:

For system layouts refer to figure 11-39.

For economic pipe selection chart refer to figure 11-38.

Find:

The most economical pipe sizes for systems (a) and (b), using portable aluminum pipe with the economic parameters considered in developing figure 11-38.

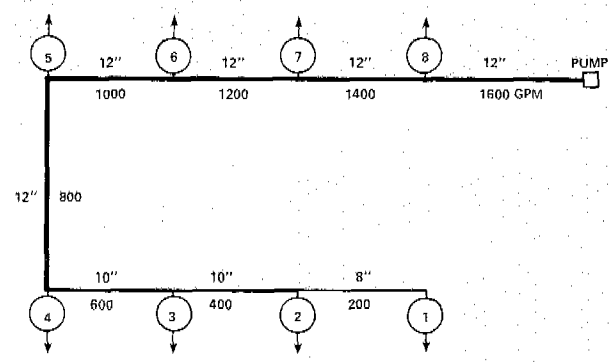
Calculation:

System (a)

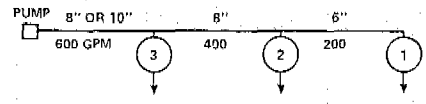
A pipe system that is to deliver 200 gpm to each of eight different hydrants as shown in figure 11-39A. The pump discharge is Q = 8 × 200 gpm = 1,600 gpm, which is also the flow rate in the first section of pipe. The flow rate in the pipe will decrease by 200 gpm at each outlet, with the final section carrying only 200 gpm. The solid dots plotted on figure 11-38 are the Q vs. q points representing this system. The pipe size region where each point falls is the pipe size to use for that section. The pipe sizes and flow rates for each reach are shown on figure 11-39A. Since 12-in pipe is the largest size considered in setting up the chart, the 12-in region is exaggerated. If 14-in pipe had been considered, perhaps some of the flows would have fallen above the 12-in region.

System (b)

Assume a system has three 200-gpm outlets so that Q = 600 gpm as shown in figure 11-39B. The square symbols plotted on figure 11-38 are the Q vs. q points representing the system. The flow rates and recommended pipe sizes for each reach are shown on figure 11-39B. If q = 200 gpm in the smaller system, 6-in pipe should be installed, and in the larger system 8-in pipe is recommended. If q = 600, the larger system should have 10-in pipe; the smaller only requires 8-in pipe. This is because the added power cost to offset friction for a given q increases with Q.



(A) 1600 – GPM SYSTEM WITH EIGHT 200 – GPM OUTLETS.



(B) 600 – GPM SYSTEM WITH THREE 200 – GPM OUTLETS.

Figure 11-39.—Flow systems with pipe sizes selected from the economic pipe size selection chart shown in figure 11-38.

The preceding examples and solutions shown in figure 11-39B are applicable for the main branch of the pipeline system when that branch is uphill, level, or moderately downhill from the pump. Many practical system layouts involve boundary conditions that differ from those given above. For these situations the trial-and-error solutions for determining the most economical pipe sizes become even more time consuming, and the chart method requires some adjustment. Some such instances are: (a) sub-branch, parallel, or branched series pipelines, and (b) pipelines running down steep slopes where the pressure gain due to elevation differences is greater than pressure loss due to friction with the pipe sizes selected by the chart method. Although in these cases the pipe sizes selected using the chart method in figure 11-38 must be adjusted downward, the adjustments are direct and yield the most economical pipe sizes for the new conditions. Sample calculation 11-34 demonstrates the use of these adjustments.

Pipe Diameter Selection.—Various designers may use different methods to size sprinkler system mainlines. The recommended technique is as follows:

1. Economic method—Selection of the least amount of fixed plus power costs as described in the section on Life-Cycle Costs.

2. Unit head-loss method—Setting a limit on the head loss per unit length, for example 2.0 ft/100 ft.

3. Velocity method—Setting a limit on the velocity.

4. Percent head loss method—Setting a limit on the friction head loss in the mainline network. This can be done by allowing mainline pressure to vary by 10 to 20 percent of the desired average sprinkler operating pressure.

For the economic method, construct an economic pipe selection chart such as figure 11-38 or by merely comparing the fixed plus power costs of the most reasonable combination of pipe sizes. In the following example all of the selection methods are compared. This sample problem demonstrates the value of the economic chart method.

Sample calculation 11-13.—Comparison of pipe-size selection methods.

Given:

For system layout refer to figure 11-40

Aluminum pipe and cost data used in previous section on *Life-Cycle Costs.*

Find:

Pipe size selection based on:

1. Economic method.
2. Head loss gradient of 2 ft/100 ft or less.
3. Maximum flow velocity of 7 ft/s or less.
4. Mainline friction head loss of 15 percent of P_a = 50 psi or 17.3 ft.

Calculations:

Selection by head loss gradient:—Select pipe sizes from table 11-18 so that the head loss gradient (J) will be less than but as close to 2 ft/100 ft as possible for each reach of pipe. This results in a total head loss of 21.4 ft due to pipe friction.

Selection by velocity method:—Select pipe sizes so that the velocity of flow will be less than but as close to 7.0 ft/s as possible for each section of pipe. This results in a total head loss of 39.7 ft due to pipe friction as shown in table 11-23. Velocity limitations for each size of pipe were computed by:

$$V = 0.4085\frac{Q}{D^2} \qquad (11\text{-}31)$$

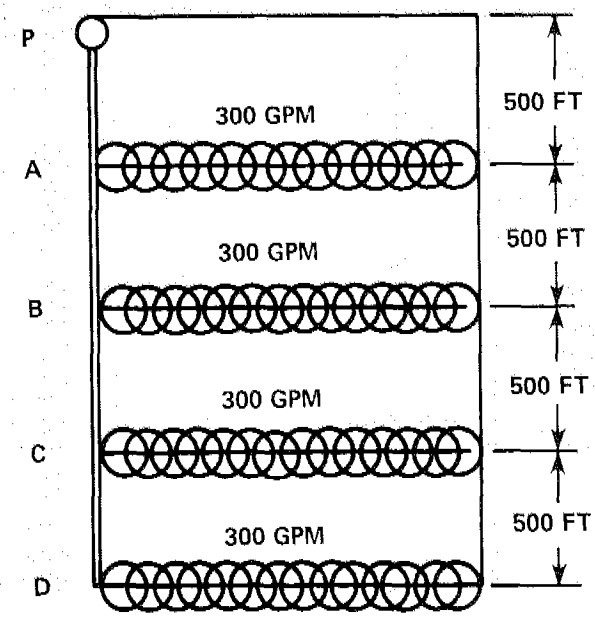


Figure 11-40.—System layout for sample calculation 11-13, as shown in table 11-23.

where

V = velocity of flow in pipe (ft/s)
Q = flow rate (gpm)
D = inside diameter of pipe (in)

Selection by percent head loss method.—Select pipe sizes so that the total head loss does not exceed 17.3 ft. For a beginning point, let the maximum unit head loss be 2.0 psi/100 ft. This will be the same as for the head loss gradient method in which the total head loss is 21.4 ft. Therefore, some pipe diameters must be increased to reduce the total head loss. First, the pipe size in the section having the greatest unit head loss should be increased; in this case the diameter in section A-B is increased from 8- to 10-in pipe. If this had not decreased the total head loss sufficiently, the pipe diameter in the section with the next highest unit head should have been increased and so on. The results of this procedure give a total head loss of 15.9 ft as shown in table 11-23.

Selection by economic method.—Select pipe sizes that will require the least amount of pumping (fuel) plus annual fixed (investment) costs as discussed earlier under Life-Cycle Costs. In this simple example the set of practical pipe diameter combinations that should be considered are:

Section	Flow (gpm)	Diameters (in)
P–A	1,200	12, 10, or 8
A–B	920	12, 10, or 8
B–C	600	10, 8, or 6
C–D	300	8, 6, or 5

This results in 28 iterations if all combinations are considered in which an upstream pipe diameter is never smaller than a downstream section.

The economic pipe selection chart presented as figure 11-38 can be used to simplify the selection process. (If the economic parameters had been different from this problem, a new chart would have been required.) This chart gives a total head loss of 5.6 ft due to pipe friction as shown in table 11-23.

Table 11-23.—Data for sample calculation 11-13 showing the total pipe friction head loss obtained by different pipe size selection methods

Pipe section	Flow gpm	Length ft	Diameter in	J ft/100 ft	Loss ft
Selection by economic method					
P–A	1,200	500	12	0.39	2.0
A–B	900	500	12	0.23	1.2
B–C	600	500	10	0.26	1.3
C–D	300	500	8	0.22	1.1
				Total	5.6
Selection by head loss gradient					
P–A	1,200	500	10	0.95	4.8
A–B	900	500	8	1.65	8.3
B–C	600	500	8	0.78	3.9
C–D	300	500	6	0.88	4.4
				Total	21.4
Selection by velocity method					
P–A	1,200	500	10	0.95	4.8
A–B	900	500	8	1.65	8.3
B–C	600	500	6	3.18	15.9
C–D	300	500	5	2.15	10.8
				Total	39.8
Selection by percent head loss method					
P–A	1,200	500	10	0.95	4.8
A–B	900	500	10	0.56	2.8
B–C	600	500	8	0.78	3.9
C–D	300	500	6	0.88	4.4
				Total	15.9

It may be surprising that such large pipe diameters are called for by the economic method in the above problem. The validity of the economic method can be tested by comparing the total annual costs of the different sets of pipes. To accomplish this the total pipe cost should be multiplied by the CRF to get the annual fixed cost. The annual energy cost (CE′) is equal to the total head loss (H_f) times the annual energy cost per unit of head loss. The CE′ can be computed by:

$$CE' = \frac{EAE\ U\ Q_s}{3{,}960} H_f \qquad (11\text{-}32)$$

where

CE′ = annual energy cost of head loss ($)
EAE = equivalent annual cost factor of escalating energy
U = present annual cost of energy from equation 29 ($/WHP-year)
Q_s = total system capacity (gpm)
H_f = total head loss due to pipe friction (ft)

Table 11-24 shows a comparison of the total annual costs for the different pipe size combinations presented in table 11-23.

From table 11-24 it is apparent that the economic selection method gives the lowest total annual cost.

An alternative to constructing and using an economic pipe selection chart is to test a unit length of each section of pipe separately. This is demonstrated in table 11-24 for section C–D in figure 11-40 in which the flow rate is only 300 gpm. However, the total system capacity must be used in equation 32 to determine the annual cost of the head loss in section C–D. This is necessary since the extra pressure head needed to compensate for the friction loss in any section of pipe must be provided at the pumping plant to the total system flow of Q_s = 1,200 gpm.

For systems with downhill or branching mainlines the pipe size selection is more complex. As a beginning point, however, pipes should be sized by the economic method. Then the pressure at each lateral inlet point should be computed to find the inlet point that requires the highest pump discharge head. Pipe sizes can then be reduced for the rest of the system so that all lateral inlet pressures are the same as demonstrated in sample calculation 11-14.

Table 11-24.—Comparison of total annual costs for different pipe size combinations for section C-D of sample calculation 11-13 (Pipe selection for section C-D)

Method (or size for C-D)	Initial capital (dollars)	Annual fixed cost[1] (dollars)	Total H (feet)	Annual energy[2] (dollars)	Annual total (dollars)
Gradient	5,000	1,070	21.4	899	1,969
Velocity	4,500	963	39.7	1,667	2,630
Percent	5,250	1,124	15.9	668	1,792
Economic	6,250	1,338	5.6	235	1,573
	$/100 ft	$/100 ft	H_f/100 ft	$/100 ft	$/100 ft
(10-inch)	300	64	0.07	3	67
(8-inch)	250	54	0.22	9	63
(6-inch)	200	43	0.88	37	80
(5-inch)	150	32	2.15	90	122

[1] CRF = 0.214 from table 11-21 for n = 15 years and i = 20%.
[2] CE′ = $42 for each foot of head loss as computed by equation 32 in which Q_s = 1,200 gpm, H_f = 1.0 ft; U = $93.33/WHP-year from equation 29 for 1,000 hr/yr, $0.07/BHP-hr and 75% pump efficiency; and EAE = 1.485 from table 11-21 for n = 15 yr, i = 20% and r = 9%.

Sample calculation 11-14.—Mainline pipe selection for a system with submains.

Given:

The economic pipe selection chart presented in figure 11-38 for aluminum pipe

A project with 4 small center pivots as shown in figure 11-41. The flow rate of each center pivot is 200 gpm.

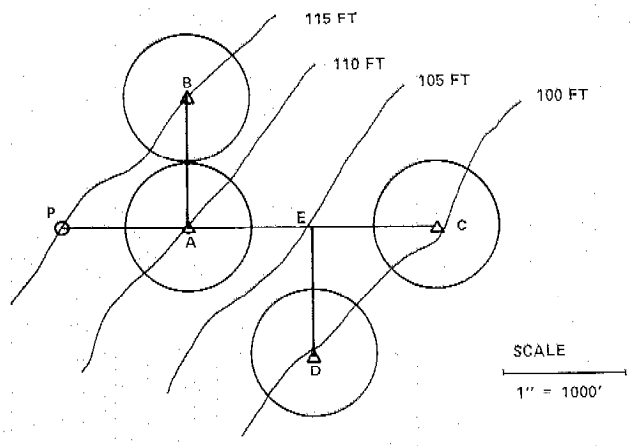


Figure 11-41.—Layout of project with four small center pivot laterals.

Find:

The most economical pipe sizes for the system

Calculations:

First select the pipe sizes from figure 11-37 and compute the friction loss in each pipe section as in table 11-25. Then locate the critical lateral inlet point as demonstrated in the top portion of table 11-26. The critical point is the inlet requiring the largest $H_f + \Delta E$, which in this case is point B. Excess pressure along the path from the pump to the critical inlet cannot be reduced by pipe size reductions. The excess pressure in all other branches, however, may be reduced if the velocity limitations are not exceeded. The excess head at C is equal to the difference between the $H^f + \Delta E1$ between P-B and P-C which is 8.7 − (−2.6) = 11.3 ft. The same amount of excess head occurs at D.

Replacing the 6-in pipe in sections E-C and E-D with 5-inch pipe still results in excess heads of 5.4 ft at C and D (see the center section of table 11-26). Therefore, a portion of the 8-in pipe in section A-E can be reduced to 6-in pipe. The length (X) of 6-in pipe that will increase the head loss by 5.4 ft can be computed by equation 24b as:

$$X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1} \times 100$$

$$= \frac{5.4}{1.50 - 0.37} \times 100 = 478 \text{ ft}$$

Replacing 478 ft of 8-in pipe with 6-in pipe in section A-E eliminates the excess head at inlets C and D as indicated in the bottom portion of table 11-26.

Table 11-25.—Friction head loss calculations in each section for sample calculation 11-14

Pipe section	Flow (gpm)	D (in)	J (ft/100 ft)	L (ft)	$h_f = J \times L/100$ (ft)
		Pipe sizes selected from economic chart			
P-A	800	10	0.45	1,000	4.5
A-B	200	6	0.42	1,000	4.2
A-E	400	8	0.37	1,000	3.7
E-C	200	6	0.42	1,000	4.2
E-D	200	6	0.42	1,000	4.2
		Next smaller set of pipe sizes			
A-E	400	6	1.50	1,000	15.0
A-B	200	5	1.01	1,000	10.1
E-C	200	5	1.01	1,000	10.1
E-D	200	5	1.01	1,000	10.1

Table 11-26.—Location of critical pivot lateral inlet and trimming sequence for sample calculation 11-14

Pipe sections	H_f (ft)	$\Delta E1$ (ft)	$H_f + \Delta E1$ (ft)	Excess (ft)
Using pipe sizes selected from economic chart				
P-A	4.5	−5	−0.5	[1]
P-A-B	4.5 + 4.2 = 8.7	0	8.7	[2]
P-A-E-C	4.5 + 3.7 + 4.2 = 12.4	−15	−2.6	11.3
P-A-E-D	4.5 + 3.7 + 4.2 = 12.4	−15	−2.6	11.3
Replacing 6-in with 5-in pipe between E-C and E-D				
P-A-E-C	4.5 + 3.7 + 10.1 = 18.3	−15	3.3	5.4
P-A-E-D	4.5 + 3.7 + 10.1 = 18.3	−15	3.3	5.4
Replacing 478 ft of 8-in pipe with 6-in pipe between A-E				
P-A-E-C	4.5 + 9.1 + 10.1 = 23.7	−15	8.7	0
P-A-E-D	4.5 + 9.1 + 10.1 = 23.7	−15	8.7	0

[1] Excess pressure at lateral inlets along critical path cannot be reduced by pipe size reductions.
[2] The critical lateral inlet is at B.

Portable Versus Buried Mainlines.—Use of buried mainlines is restricted to areas that are to be irrigated permanently, whereas portable mainlines can be used on all areas. Aside from this restriction on the use of mainlines, the choice between portable and buried mains and between different pipe materials is largely a matter of economics.

No installation costs are involved in portable mainlines. They can be moved about, and in most

Buried mainlines have some distinct advantages over portable mainlines and because materials used in buried mainline pipe are not handled after initial installation, this type of line has a much longer life. Thus, for the same length and size of mainline, the annual fixed cost for buried mainlines is usually lower than that for portable lines. There is a considerable saving in the labor that is required to move portable lines within the design area and to and

rial, and then determine the total annual cost (fixed, energy, maintenance, labor) of the mainline portion of each system.

Design for Continuous Operation.—Most irrigators prefer a sprinkler system that may be operated continuously without having to stop the pump each time a lateral line is uncoupled and moved to the next position. With portable mainlines, valve-tee couplers are placed at each lateral position, and each lateral line is equipped with a quick-coupling valve opening elbow. The elbows on the laterals open and close the valves in the couplers, thus permitting the flow of water from the main to be turned on or off at will. If buried mainlines are used, takeoff or hydrant valves are placed on top of the riser and serve the same purpose as the valve-tee couplers in portable lines.

One or more extra lateral lines are often used so that they may be moved from one position to another while others are in use, thereby permitting uninterrupted operation. This type of operation offers several advantages. It eliminates long walks to the pump and back each time a lateral line is uncoupled and moved, and it takes fewer people, one or two, to move one lateral line while the other lines are running, so a relatively large system can operate continuously.

Pressure Requirements

To select a pump and power unit that will operate the system efficiently, determine the total of all pressure losses in the system. This yields the total dynamic head against which water must be pumped. Sketches showing the various losses that contribute to the total dynamic head are shown for both centrifugal and turbine pumps in Chapter 8, *Irrigation Pumping Plants*.

If operating conditions vary considerably with the movement of laterals and mainline, or with a change in the number of sprinklers operated, both the maximum and minimum total dynamic head (TDH) must be computed.

Losses in Fittings and Valves.—Allowance must be made for friction losses in all elbows, tees, crossings, reducers, increasers, adapters, and valves placed in laterals, mainlines, or submains and in the suction line. Where deep-well turbine pumps are used, losses in the column must be considered. Pump manufacturers make allowances for losses in the pump itself.

Losses in fittings and valves are computed by:

$$h_f = K \frac{V^2}{2g} \qquad (11\text{–}33)$$

where

h_f = friction head loss (ft)
K = resistance coefficient for the fitting or valve

$\frac{V^2}{2g}$ = velocity head for a given discharge and diameter (ft)

Values of the resistance coefficient (K) may be taken from table 11–27 for irrigation pipe or table 11–28 for standard pipe fittings and valves. The velocity head may be computed by:

$$\frac{V^2}{2g} = 0.002592 \frac{Q^2}{D^4} = \frac{Q^2}{386\ D^4} \qquad (11\text{–}34)$$

where

Q = flow rate (gpm)
D = inside diameter of pipe (in)

When determining the velocity head at a reducing fitting, the diameter and flow that gives the highest head should be used. As an example assume an 8-x6-x6-in reducing side outlet tee has an inflow of 1,000 gpm and outflows of 400 gpm from the side outlet and 600 gpm through the body. The three respective velocity heads are 0.64 ft for the inlet, 0.32 ft for the side outlet, and 0.69 ft for the line flow through the body. Therefore, when estimating h_f for the side outlet flow, use the velocity head of 0.64 ft (since it is larger than 0.32 ft) and $K = 1.0$ from table 11–27 to obtain $h_f = 0.64 \times 1.0 = 0.64$ ft (by eq. 33). For the line flow $h_f = 0.5 \times 0.69 = 0.35$ ft.

Table 11–29 gives velocity heads for inside diameters in whole inch increments. Actual inside pipe diameters are usually different, but these table values give satisfactory results for most practical purposes. The values of K are only approximations for the fittings in general, inasmuch as the inside diameters of fittings vary as well.

Figure 11–42 is a nomograph that can be used to simplify estimating losses in fittings and valves. Sample calculation 11–15 demonstrates the use of the nomograph.

Table 11-27.—Values of resistance coefficient (K) for irrigation pipe fittings and valves [1]

Fitting or valve	Diameter (in)							
	2	3	4	5	6	8	10	12
Couplers								
ABC	1.2	0.8	0.4	0.3				
Hook latch	0.6	0.4	0.3	0.2	0.2			
Ring lock				0.2	0.2	0.2	0.2	0.2
Elbows								
Long radius	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Mitered	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.5
Tees								
Hydrant (off)		0.6	0.5	0.4	0.3	0.3	0.3	0.3
Side outlet	1.6	1.3	1.2	1.1	1.0	0.9	0.8	0.8
Line flow	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4
Side inlet	2.4	1.9	1.7	1.5	1.4	1.2	1.1	1.1
Valves								
Butterfly					0.8	0.6	0.5	0.5
Plate type	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Ames check			1.8		1.5	1.3	1.2	
Hydrant with opener		8.0	7.5	7.0	6.7			
Special								
Strainer	1.5	1.3	1.0	0.9	0.8	0.7	0.6	0.5
"Y" (Long rad.)	0.8	0.6	0.6	0.6	0.4	0.4	0.3	0.3

[1] Source: Ames Irrigation Handbook. W. R. Ames Company, Milpitos, Calif.

Sample calculation 11-15.—Use of nomograph for estimating fitting losses.

Given:

The nomograph for estimating fitting losses, figure 11-42

Mainline: Q = 450 gpm; D = 6 in

Fitting: Plate valve

Find:

The head loss resulting from the valve

Calculations:

From table 11-27 K = 2.0

Start from the left on the nomograph with 6-in pipe diameter passing through 450 gpm on the flow rate line. This line intersects the third scale at a flow velocity of 5.1 ft/s.

Draw a line from the flow velocity through the pivot point to intersect the velocity head at 0.38 ft.

Draw a line from this velocity head through K = 2.0 to the right-hand scale and reach the head loss, h_f = 0.76 ft.

Static Head.—Static head is the vertical distance ($\Delta E1$) the water must be raised or lowered between the water source and the point of discharge. Static head may be plus or minus.

Static head in laterals has been considered in the design procedure for determining the lateral inlet pressure (P_m) required for proper operation and, therefore, need not be considered here.

The differences in elevation between the pump and the highest and lowest points on the mainline or submain give the maximum and minimum static head values. These must be included in computing the total dynamic head for maximum and minimum operating conditions.

Suction lift, or the difference between the elevation of the water source and the elevation of the pump, is a form of static head that must be included in total head computations. For wells, the drawdown while pumping at the maximum required discharge should also be included in the figure for suction lift.

Velocity Head—Since the velocity of flow in a sprinkler system seldom exceeds 8 feet per second, the velocity head seldom exceeds 1 ft and therefore may be disregarded.

Total Dynamic Head.—The total dynamic head (TDH) is the sum of the following:

Pressure head required to operate lateral (P_m), ft

Friction head losses in mainline and submains (H_f), ft

Friction head losses in fittings and valves (Σh_f), ft

Total static head including suction lift ($\Delta E1$), ft

Table 11-28.—Values of resistance coefficient (K) for standard pipe fittings and valves

Fitting or valve	Nominal diameter							Source or authority
	3-in	4-in	5-in	6-in	7-in	8-in	10-in	
Elbows:								
Regular flanged 90°	0.34	0.31	0.30	0.28	0.27	0.26	0.25	Pipe friction manual [1]
Long radius flanged 90°	.25	.22	.20	.18	.17	.15	.14	Hydraulic Institute
Long radius flanged 45°	.19	.18	.18	.17	.17	.17	.16	..... do .....
Regular screwed 90°	.80	.70						..... do .....
Long radius screwed 90°	.30	.23						..... do .....
Regular screwed 45°	.30	.28						..... do .....
Bends:								
Return flanged	0.33	0.30	0.29	0.28	0.27	0.25	0.24	Pipe friction manual [1]
Return screwed	.80	.70						Hydraulic Institute
Tees:								
Flanged line flow	.16	.14	.13	.12	.11	.10	.09	..... do .....
Flanged branch flow	.73	.68	.65	.60	.58	.56	.52	..... do .....
Screwed line flow	.90	.90						..... do .....
Screwed branch flow	1.20	1.10						..... do .....
Valves:								
Globe flanged	7.0	6.3	6.0	5.8	5.7	5.6	5.5	..... do .....
Globe screwed	6.0	5.7						..... do .....
Gate flanged	.21	.16	.13	.11	.09	.075	.06	..... do .....
Gate screwed	.14	.12						..... do .....
Swing check flanged	2.0	2.0	2.0	2.0	2.0	2.0	2.0	..... do .....
Swing check screwed	2.1	2.0						..... do .....
Angle flanged	2.2	2.1	2.0	2.0	2.0	2.0	2.0	..... do .....
Angle screwed	1.3	1.0						..... do .....
Foot	.80	.80	.80	.80	.80	.80	.80	..... do .....
Strainers-basket type	1.25	1.05	.95	.85	.80	.75	.67	..... do .....
			Other					
Inlets or entrances:								
Inward projecting	0.78		All diameters					King's Handbook [1]
Sharp cornered	.50		All diameters					..... do .....
Slightly rounded	.23		All diameters					..... do .....
Bell-mouth	.04		All diameters					..... do .....
Sudden enlargements	$K = \left(1 - \frac{d_1^2}{d_2^2}\right)^2$ where d_1 = diameter of smaller pipe							S.I.A. Handbook [2]
Sudden contractions	$K = 0.7\left(1 - \frac{d_1^2}{d_2^2}\right)^2$ where d_1 = diameter of smaller pipe							S.I.A. and King

[1] King, Horace Williams, and Ernest F. Brater, 1963. Handbook of Hydraulics. McGraw Hill Book Co., Inc.
[2] Pair, Claude H., Walter W. Hinz, Crawford Reid, and Kenneth R. Frost. 1975. Sprinkler Irrigation. Sprinkler Irrigation Assoc. Brantwood Publishers, Inc.

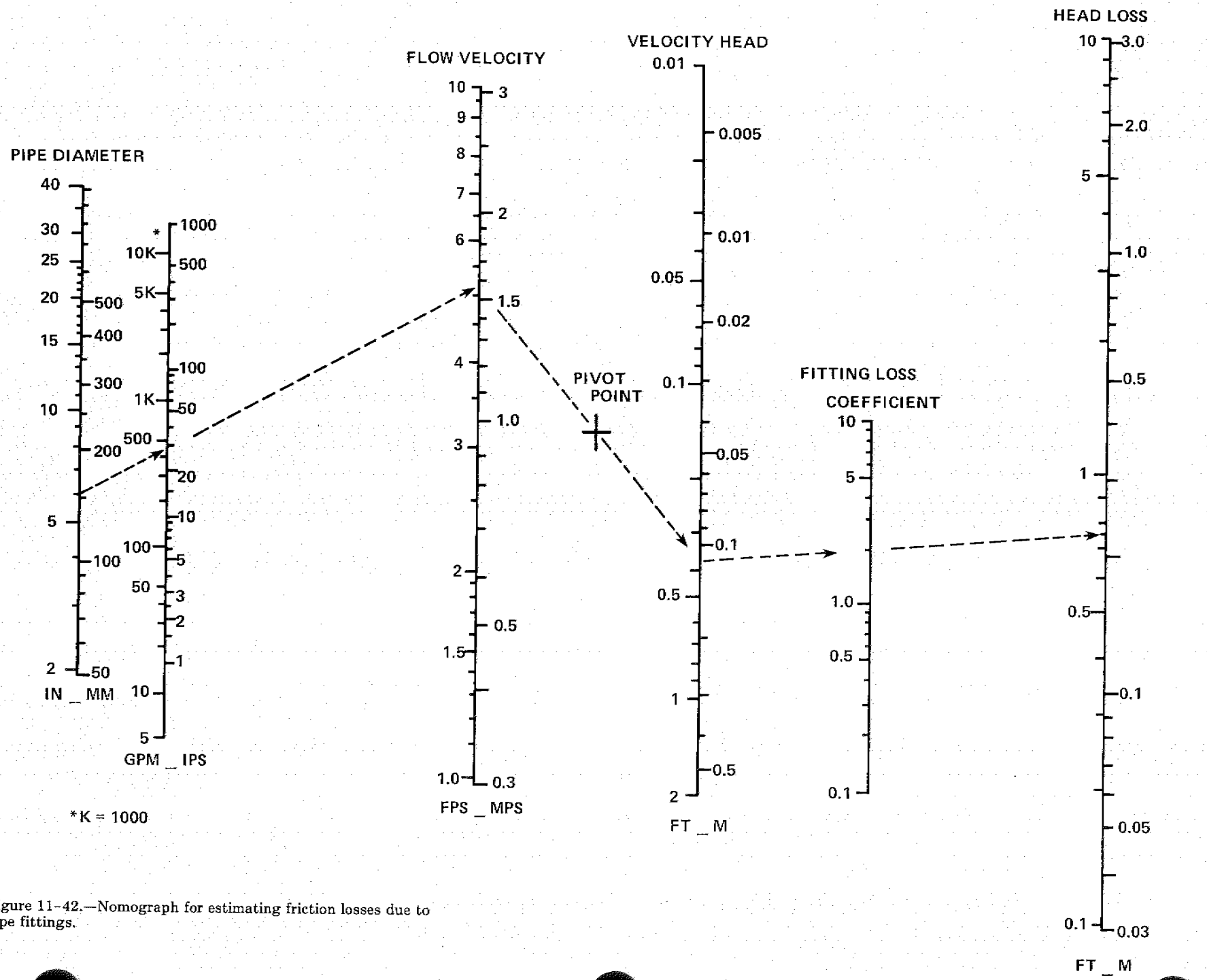


Figure 11-42.—Nomograph for estimating friction losses due to pipe fittings.

Table 11-29. Values of velocity head ($V^2/2g$) in feet, for different diameters and flow rates

Flow (gpm)	Inside diameter (in) 2	3	4	5	6	7	8	10	12
100	1.62	0.32	0.10	0.04	0.02				
150	3.64	0.72	0.23	0.09	0.04				
200	6.48	1.28	0.40	0.17	0.08				
250		2.00	0.63	0.26	0.12				
300		2.88	0.91	0.37	0.18	0.10	0.06		
350		3.92	1.24	0.51	0.24	0.13	0.08		
400		5.12	1.62	0.66	0.32	0.17	0.10		
450		6.48	2.05	0.84	0.40	0.22	0.13		
500		8.00	2.53	1.04	0.50	0.27	0.16	0.06	
550		9.68	3.06	1.25	0.60	0.33	0.19	0.07	
600			3.64	1.49	0.71	0.39	0.23	0.09	
650			4.28	1.75	0.84	0.46	0.27	0.11	
700			4.96	2.03	0.98	0.53	0.31	0.13	0.06
750			5.69	2.33	1.12	0.61	0.36	0.15	0.07
800			6.48	2.65	1.28	0.69	0.41	0.17	0.08
850			7.31	2.99	1.44	0.78	0.46	0.19	0.09
900			8.20	3.36	1.62	0.87	0.52	0.21	0.10
1000				4.15	2.00	1.08	0.64	0.26	0.13
1100				5.02	2.42	1.31	0.77	0.31	0.15
1200				5.97	2.88	1.55	0.92	0.37	0.18
1300				7.01	3.38	1.82	1.07	0.44	0.21
1400				8.12	3.92	2.11	1.25	0.51	0.25
1500				9.33	4.50	2.43	1.42	0.58	0.28
1600					5.12	2.75	1.64	0.66	0.32
1800					6.48	3.49	2.01	0.84	0.41
2000					8.00	4.32	2.53	1.04	0.50
2200					9.68	5.22	3.06	1.25	0.61
2400						6.22	3.64	1.49	0.72
2600						2.29	4.28	1.75	0.84
2800						8.46	4.96	2.03	0.98
3000						9.71	5.69	2.33	1.12
3200							6.47	2.65	1.28

Miscellaneous losses (for safety) usually taken as 0.2 H_f, ft

Sample calculation 11-16 demonstrates the computation of the TDH for a simple sprinkle system.

Sample calculation 11-16.—Determining the TDH for a sprinkle system.

Given:

The system layout shown in figure 11-43
Lateral: Flow rate 300 gpm, P_m = 50 psi
Mainline: PVC plastic pipe, IPS, SDR, 41
System Capacity: Q = 900 gpm

Find:

The total dynamic head (TDH) required at the pump discharge.

Calculations:

In figure 11-43 the critical lateral is at D and the pressure head required at the inlet is:

$P_m \times 2.31 = 50 \times 2.31 = 115.5$ ft

The friction loss in the mainline between P and D using J values from table 11-19a is:

Section P-B	0.98 × 1000/100	= 9.8 ft
Section B-C	1.67 × 500/100	= 8.4
Section C-D	0.47 × 500/100	= 2.4
Total		H_f = 20.6 ft

The friction head loss in the fittings based on K values from table 11-27 and velocity head values from table 11-29:

Velocity heads are:

Section P-B	0.52 ft
Section B-C	0.71 ft
Section C-D	0.18 ft
4-in hydrant	0.91 ft

The fitting losses in section P-B:

1 check valve	1.3 × 0.52	= 0.7 ft
2 mitered elbows	2 (0.6 × 0.52)	= 0.6
4 hydrants (off)	4 (0.3 × 0.52)	= 0.6
1 line flow tee	0.5 × 0.52	= 0.3

The fitting losses in section B-C:

4 hydrants (off)	4 (0.3 × 0.71)	= 0.9
1 line flow tee	0.5 × 0.71	= 0.4

The fitting losses in section C-D:

4 hydrants (off)	4 (0.3 × 0.18)	= 0.2

The fitting loss of D:

1 hydrant with opener	7.5 × 0.91	= 6.8
Total		h_f = 10.5 ft

The static head between P and D is

Section P-B	1.5% × 1,000/100	= 15.0
Section B-D	1.0% × 1,000/100	= 10.0
Total		ΔE1 = 25.0

can be solved very simply from equation 35b. The pressure head (P) may be in either pounds per square inch or feet, as K_s will assume the necessary conversion factors.

The spacing between lateral moves that will give a constant average application rate can be determined easily for various pressure heads by solving equation 35b, using the K_s as determined above, and the pressure head available at the lateral inlet. For example, a standard lateral inlet pressure of 50 psi and a lateral move of 60 ft are selected for a given gravity sprinkler irrigation system. Thus $K_s = 60/\sqrt{50} = 8.48$. When the pressure at the head of the lateral is only 45 psi because of insufficient elevation differentials, the lateral spacing should be $S_m = 8.48\sqrt{45} = 57$ ft to give the same average application rate. For 40 psi, the spacing should be 54 ft; for 30 psi, 47 ft; and for 20 psi, 38 ft.

The above procedures have been found useful for the design of the lateral line spacing of gravity sprinkler systems. The designer is provided with a quick method for determining the lateral spacing, which will yield a constant application rate in areas where below-normal operating pressures are encountered. Care must be taken, however, that pressures selected furnish sufficient jet breakup and sprinkler rotation.

Selection of Pump and Power Unit

Having determined the range of operating conditions (maximum and minimum capacities and total dynamic heads), the pump and power unit may be selected according to the procedures in Chapter 8, *Irrigation Pumping Plants.*

Horsepower Required.—The horsepower required to operate a sprinkler system can be computed by:

$$BHP = \frac{Q_s \times TDH}{3{,}960\ E_p/100} \qquad (11\text{-}36)$$

where

BHP = brake horsepower required to operate pump (hp)
Q_s = system capacity (gpm)
TDH = total dynamic head (ft)
E_p = pump efficiency (%)

Seasonal Power Cost.—The annual cost of power to operate the pumping unit can be computed by:

$$CE = \frac{UQ_s\ TDH}{3{,}960} \qquad (11\text{-}37)$$

where

CE = present annual energy cost to operate system ($)
U = present annual cost of energy from equation 29 ($/WHP-year)

To determine the average annual energy cost over the economic life of the system, taking into account the time value of money and anticipated energy inflation rate, multiply CE by EAE (from table 11-21 or equation 27).

Field Test Data

Successful operation of sprinkle irrigation systems requires that the frequency and quantity of water application be accurately scheduled. Field application efficiency must be known to manage the quantity of application. Since system performance changes with time, periodic field checks are recommended. Data from the field evaluation of a periodic move sprinkle system were presented in figure 11-24. The procedure for collecting the data follows:

Information Required.—The desired information includes:

1. Duration of normal irrigations.
2. Spacing of sprinklers along lateral lines.
3. Spacing of lateral lines along mainlines.
4. Measured depths of water caught in catch containers at a test location.
5. Duration of the test.
6. Water pressures at the sprinkler nozzles at the test location and along laterals throughout the system.
7. Rate of flow from the tested sprinklers.
8. Additional data specified on figure 11-44.

It is useful to know what wetting patterns the operation produces at different pressures and also to know operating pressures at the pump and along the mainline and laterals. General study of data obtained in the field enables determination of system DU and E_q. Further study enables determination of the uniformity and economics of the spacings, the economics of sizes of pipes used for mains and laterals, the desirability of using other operating pressures and other durations of application, and the effect of wind.

1. Location _____, observer _____, date _____
2. Crop _____, root zone depth ___ ft, MAD ___ %, MAD ___ in
3. Soil: texture _____, available moisture ___ in/ft, SMD ___ in
4. Sprinkler: make _____, model ___, nozzles ___ by ___ in
5. Sprinkler spacing ___ by ___ ft, irrigation duration ___ hr
6. Rated sprinkler discharge ___ gpm at ___ psi giving ___ in/hr
7. Lateral: diameter ___ in, slope ___ %, riser height ___ in
8. Actual sprinkler pressure and discharge rates:

	Sprinkler location number on test lateral					end
Initial pressure (psi)						
Final pressure (psi)						
Catch volume (gal)						
Catch time (min or sec)						
Discharge (gpm)						

9. Wind: direction relative to
   Part 10: initial ___, during ___, final ___
   Speed (mph): initial ___, during ___, final ___
10. Container grid test data in units of ___, volume/depth ___ ml/in
    Container grid spacing ___ by ___ ft
    Test: start ___, stop ___, duration ___ hr ___ min = ___ hr

11. Evaporation container: initial ___ final ___ loss ___ in
12. Sprinkler pressures: max ___ psi; min ___ psi, ave ___ psi
13. Comments _____

Figure 11-44.—Sprinkler-lateral irrigation evaluation.

Equipment Needed.—The equipment the evaluator needs is:

1. A pressure gauge (0-100 psi) with pitot tube attached (See fig. 11-45.)
2. A stopwatch or watch with an easily visible second hand.
3. A large container clearly marked (1 gal or larger for large sprinklers).
4. A 4-ft length of flexible hose of inside diameter appreciably larger than the outside diameter of nozzles. (See fig. 11-46.)
5. From 50 to 100 (or more depending on sprinkler size) catch containers such as 1-qt oil cans or plastic freezer cartons.
6. A measuring stick (or ruler) to measure depth, or a 500-ml graduated cylinder to measure water caught in containers.
7. A soil probe or auger.
8. A 50- or 100-ft tape for measuring distances in laying out catch container grid.
9. A shovel for smoothing spots to set containers and for checking soil, root, and water penetration profiles.

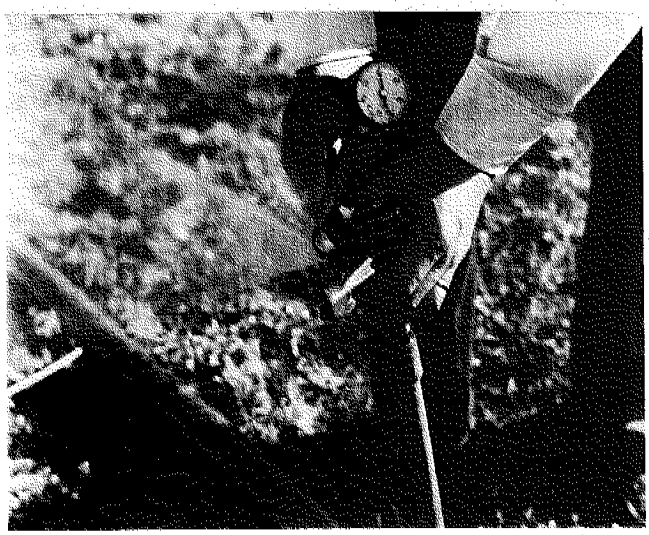


Figure 11-45.—Measuring pressure at sprinkler nozzle with gage connected to pitot tube.

Figure 11-46.—Measuring sprinkler discharge using a hose to direct the water into a container.

10. A form (fig. 11-44) for recording data.

11. Manufacturers' sprinkler performance charts showing the relationship between discharge, pressure, and wetted diameter plus recommended operating pressure ranges.

12. A set of drill bits ranging from 3/64- to 1/4-in in diameter in increments of 1/64-in to check nozzle wear.

Field Procedure.—The information obtained from the following field procedure should be entered in a data sheet similar to figure 11-44.

1. Choose a location along a lateral for the test. It may be either a single location at which the pressure is representative of the entire system, or two locations near the ends of a lateral to permit study of effects of differences in pressure. Loss of pressure due to friction in a lateral that has only one size of pipe is such that about half of the pressure loss occurs in the first 20 percent of the length and over 80 percent occurs in the first 50 percent of the lateral's length (fig. 11-47). On a flat field the most representative pressure is at about 40 percent of the distance from the inlet to the terminal end.

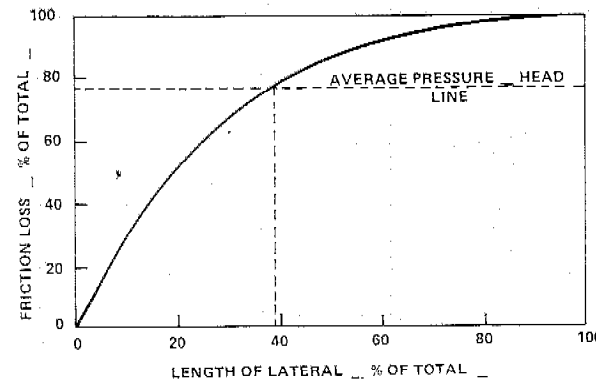


Figure 11-47.—Loss of pressure due to friction along a lateral having only one size of pipe.

2. Set out at least 24 catch containers (see pattern in fig. 11-48) on a grid having a spacing not to exceed 10- by 10-ft for testing along a single lateral line. The catch containers' pattern should be laid out to cover two adjacent areas between three sprinklers, since sprinklers may not apply water at precisely uniform rates. Each catch container is assumed to give the representative depth of catch over the square having the same dimensions as the can spacing in which it is centered. (See dotted grid lines in fig. 11-48.)

For solid set or block move systems where several adjacent laterals operate simultaneously, the catch containers should be placed in the area between two adjacent laterals. Caution should be exercised to allow for any water that could enter the test container area from adjacent blocks. These tests cannot be used to study other lateral spacings.

Each container should be located within a foot of its correct grid position and carefully set in an upright position with its top parallel to the ground; any surrounding vegetation that would interfere with a container should be removed. When it is

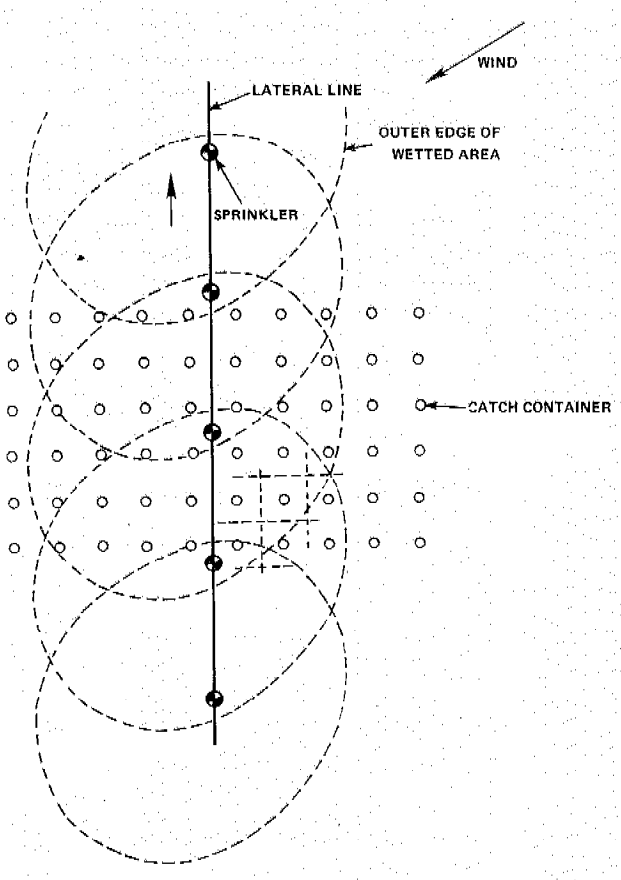


Figure 11-48.—Layout of catch containers for testing the uniformity of distribution along a sprinkler lateral line.

windy, it may be necessary to fasten containers to short stakes with rubber bands and weight them with a known depth of water (which is later subtracted from the total depth shown after the catch) or with a stone, or they may be set in shallow holes. The most accurate means for measuring the catch can be achieved volumetrically by using a graduated cylinder. These measurements can be converted to depths if the area of the container opening is known. For 1-qt oil cans, 200 ml corresponds to 1 in. in depth. Other suitable catch containers may be square or cylindrical plastic freezer containers with sides tapered slightly for nesting, or any similar container.

Determine and record the container grid spacing and the ratio of volume to depth of catch. Also indicate the position of the lateral and record the location and position numbers of the sprinklers on the lateral. (See fig. 11-44; part 10.)

3. Determine the soil texture profile and management allowed deficit (MAD) then estimate the available soil moisture capacity in the root zone and check the soil moisture deficit (SMD) in the catch area on the side of the lateral that was not irrigated during the previous set. These values should be recorded in parts 2 and 3.

4. Check and record the make and model of the sprinkler and the diameter of the nozzles.

5. Obtain the normal sprinkler spacing, duration, and frequency of irrigation from the operator and record them. The standard way of expressing the sprinkler grid spacing is__ by__ feet; this indicates the sprinkler spacing on the lateral and the spacing between laterals in that order.

6. Read and record the rated sprinkler discharge, pressure, and the computed average design application rate from the system design data and manufacturer's sprinkler catalogs.

7. Check and record the size and slope of the lateral pipe and the height and erectness of the risers.

8. Before starting the test, stop the rotation of the sprinklers at the test site by wedging a short piece of wire or stick behind the swinging arm.

Turn on the water to fill the lateral lines. When the test lateral is full, turn the pressure up slowly to observe the trajectory, breakup of drops, and effect of wind at different pressures. Then set the pressure at the value desired for the test.

Measure and record the pressure at sprinklers at several places along the line and at both ends of the line to observe the differences in pressure. Pressures should be checked at both the beginning and end of the test period and recorded in part 8. When measuring sprinkler pressures (fig. 11-45), the pitot tube must be centered in the jet, which must impinge directly onto its tip. The tip may be rocked slightly. Record the highest pressure reading shown while the pitot tube is being held about 1/8-in from the sprinkler nozzle.

Also in part 8, record how long it takes each sprinkler in this test area to fill the large container of known volume. Do this by slipping a short length of hose over the sprinkler nozzle and collecting the flow in the container (fig. 11-46). To improve accuracy, measure the nozzle output several times and take the average. (If the sprinkler has two nozzles, each can be measured separately with one hose.) Often the measured sprinkler discharge rate is greater than that specified by the manufac-

turer at the given pressure. This occurs because sprinkler nozzles often become enlarged during use, or because the hose fits too tightly and creates a syphoning action. You can check nozzle erosion with a feeler gauge such as a drill bit that has the diameter specified for the nozzle.

9. Note the wind speed and direction and record the wind direction in part 9 by drawing an arrow in the direction of water flow in the lateral.

10. Empty all catch containers before starting the test; start the test by removing the wires or sticks and releasing all sprinklers surrounding the test site so they are free to rotate. Note the starting time in part 10.

11. Set outside the catchment area a container holding the anticipated amount of catch to check the approximate volume of water lost by evaporation. (See fig. 11-44, part 10.)

12. While the test is in progress, check sprinkler pressures at 20 to 40 judiciously selected locations throughout the system (for example, at the two ends and quarter points along each lateral) and record in part 12 the maximum, minimum, and average pressures.

13. Terminate the test by either stopping the sprinklers surrounding the test site in a position so that the jets do not fall into the containers, or by deflecting the jets to the ground. Note the time, check and record the pressure, and turn off the water. It is most desirable for the duration of the test to be equal to the duration of an irrigation to get the full effect of wind and evaporation. Ideally minimum duration tests should apply an average of about 0.5 in of water in the containers.

Measure the depth of water in all the containers and observe whether they are still upright; note any abnormally low or high catches. As shown in part 10, depths or volumes caught are recorded above the line at the proper grid point, which is located relative to the sprinkler and direction of flow in the pipe line. For long runs, where maximum depths exceed 2 in., a measuring stick provides suitable accuracy up to ± 0.1 in.

Use of Field Data.—Use of the data was discussed in connection with the test data presented in figure 11-24. The general procedure for analyzing the data is:

1. Convert the depths or volumes of water caught in the containers to application rates and record them (iph) below the line on part 10 of the data sheet. Assuming that the test is representative and that the next set would give identical results, the right-hand side of the catch pattern may be overlapped (or superimposed) on the left-hand side (fig. 11-25), as if it were a subsequent set, to simulate different lateral spacings. For lateral spacings that are whole units of the container spacings, the sum of the catches of the two sets represents a complete irrigation. For very close lateral spacings, water may overlap from as many as four lateral positions. The simulation of overlapping discussed above is not recommended where winds are likely to change appreciably between subsequent lateral sets. It is most useful for 24-hour sets.

2. To determine whether sprinklers are operating at acceptable efficiency, evaluate system DU and CU using equations 3, 4, and 11. The system DU is based on the average rate or depth recorded for the lowest one-fourth of the catch locations; hence, about one-eighth of the area may actually have received slightly less water. If an individual low value was due to a poor field measurement, perhaps no area actually received less. If the average low quarter depth infiltrated just matches the SMD, the percent of the infiltrated water going too deep would be approximately equal to 100 − system DU. (A similar relationship exists for CU.)

3. The potential system application efficiency (E_q and E_h) should be determined to evaluate how effectively the system can use the water supply and what the total losses may be. The total amount of water required to fully irrigate the field can be estimated.

The E_q and E_h values are always a little lower than the DU and CU of a sprinkle irrigation system because the average water applied is greater than the average water caught. The difference between the water applied and the water caught approximates losses due to evaporation and drift, loss of water from ungauged areas, and evaporation from the gage cans. The system E_q and E_h indicate how well the tested sprinklers can operate if they are run the correct length of time to satisfy the SMD or MAD. It is, therefore, a measure of the best management can do and should be thought of as the potential of the system, assuming that the test area truly represents the whole field.

The effective portion of applied water (R_e) (used in equations 7 and 8 for computing E_q and E_h) can be determined from the field data by:

$$R_e = \frac{\text{average catch rate (or depth)}}{\text{application rate (or depth)}} \qquad \textbf{(11-38a)}$$

$$R_e = \frac{\text{average catch rate}}{96.3\ q/(S_\ell \times S_m)} \qquad \textbf{(11–38b)}$$

where

q = average sprinkler discharge rate (gpm)
S_ℓ = sprinkler spacing on the lateral (ft)
S_m = lateral spacing along the main (ft)

Traveling Sprinkle System

A typical traveling sprinkle system consists of the following major components: pumping plant, mainline, flexible hose, traveler unit, and gun sprinkler (fig. 11–8). The general design procedure, system capacity requirements, depth of application, optimum application rates, and irrigation efficiency criteria are developed in the section on *Planning Concepts*. The selection of pumping plants and mainline designs is presented in the section on *Periodic-Move and Fixed-Systems*.

Sprinkler and Traveler Selection

Sprinkler characteristics that need to be considered are nozzle size and type, operating pressure, jet trajectory, and sprinkler body design. The operating conditions that enter into the selection process are soil infiltration characteristics; desired depth and frequency of irrigation; towpath length, potential towpath spacings and number of paths for each potential spacing; wind conditions; crop characteristics; and the mechanical properties of the soil.

Sprinkler Variables.—Gun sprinklers used in most travelers have trajectory angles ranging between 18° and 32°. When operating at relatively low pressures, higher trajectory angles increase the altitude of the jet, which allows the stream to exhaust its horizontal velocity before the water droplets reach the soil surface. Therefore, the higher angles give maximum coverage in low winds, and droplet impact is minimized. The low angles give more uniform coverage in winds above 10 mph, but drop impact is quite severe and may be detrimental to all but the sturdiest crops and coarsest soils. For average conditions trajectories between 23° and 25° are satisfactory. These midrange trajectories give reasonable uniformity in moderate winds, have gentle enough drop impact for most crops and soils, and are suitable for operation on varying slope conditions where there will be some riser tilting.

Most gun sprinklers used on travelers can be fitted with either tapered or orifice-ring nozzles. The tapered nozzles normally produce a compact water jet that is less susceptible to wind distortion than the more diffuse stream from a ring nozzle. Therefore, for a given discharge the tapered nozzles will also provide a greater distance of throw, which may permit wider towpath spacing and lower application rates. Ring nozzles, however, produce better stream breakup at lower operating pressures, which is an important factor on delicate crops. Furthermore, ring nozzles offer considerably greater flexibility in nozzle size selection at low cost.

Some irrigators may prefer to begin the irrigation season with small nozzles at high pressure that generate ideal droplet conditions during the critical germination or blossom stages. As the season progresses, the orifice size can be increased to meet greater crop demands during the peak moisture consumption period. At that time, the ground is normally covered with foliage, and the larger water droplets will not adversely affect production or soil tilth.

Typical nozzle discharges and diameters of coverage are presented in table 11–30 for gun sprinklers with 24° angles of trajectory and tapered nozzles. The wetted diameter would increase, or decrease, about 1 percent for each 1° change in trajectory angle. Ring nozzles sized to give similar discharges at the same pressures would produce diameters that are about 5 percent smaller than those presented in table 11–30.

Both full-circle and part-circle gun sprinklers are available in all nozzle types and size ranges. Some sprinklers need to be operated with part circle coverage to give even water distribution, a dry path for vehicle travel, or both. The use of part-circle sprinklers increases the application rate. A half-circle coverage will double the full-circle application rate of the same sprinkler operating under similar conditions.

Gun sprinklers tend to produce Christiansen's "E" type profiles (fig. 11–23). Since the traveling sprinklers operate independently, the actual application rate at which water must infiltrate into the soil to eliminate runoff is approximately:

$$I_t = \frac{96.3\ q}{\pi\,(0.9_t)^2} \times \frac{360}{\omega} \qquad \textbf{(11–39)}$$

Table 11-30.—Typical discharges and wetted diameters for gun sprinklers with 24° angles of trajectory and tapered nozzles operating when there is no wind

	Tapered nozzle size (in)									
	0.8		1.0		1.2		1.4		1.6	
Sprinkler pressure	Sprinkler discharge and wetted diameter									
psi	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft
60	143	285	225	325	330	365	—	—	—	—
70	155	300	245	340	355	380	480	435	—	—
80	165	310	260	355	380	395	515	455	675	480
90	175	320	275	365	405	410	545	470	715	495
100	185	330	290	375	425	420	575	480	755	510
110	195	340	305	385	445	430	605	490	790	520
120	205	350	320	395	465	440	630	500	825	535

where

I_t = approximate actual application rate from a traveling sprinkler (iph)
q = sprinkler discharge (gpm)
t = wetted radius (ft)
ω = portion of circle receiving water (degrees)

This is similar to equation 2. The wetted area is based on only 90 percent of the radius of throw to give the approximate application rate over the major portion of the pattern rather than the average rate over the whole wetted area. Using data from table 11-30 in equation 39, the actual application rates from 0.8-in and 1.6-in nozzles operating full-circle at 80 psi are 0.26 iph and 0.44 iph, respectively. Using ring nozzles that would reduce the wetted diameters by about 5 percent would increase the application rate to approximately 0.29 iph and 0.49 iph, respectively. For a tapered nozzle operating with a 25° dry wedge as in figure 11-9, the application rates would be increased to 0.33 iph and 0.56 iph, respectively.

Traveler.—The traveler selected should provide the required flow rate and power to drag the hose at the travel speeds necessary to meet the design criteria. Controls to provide a uniform speed of travel that will not vary more than ± 10 percent as the traveler moves from one end of the field to the other and positive shutoff at the end of travel are essential.

Constant travel speed is required for uniform water distribution over the irrigated area. Some of the factors that affect the ability of a traveler to maintain constant speed are:

1. Hose pull, which varies with hose size, soil type, terrain, and condition of the towpath.
2. Water pressure and flow rate.
3. Amount of cable buildup on the cable reel varies with the design of the cable drum and must be compensated for in the design of the traveler, or the machine will speed up through the travel run.
4. The characteristics of the power unit on the traveler must be matched to the requirements of hose pull and other factors enumerated above for operation at a constant speed.

Many of the above factors vary by as much as 200 to 300 percent, depending upon location, and the design and operation of the traveler must include the capability to handle such variations.

The end pull required to drag a hose depends on the soil texture, soil moisture conditions, and crop cover. Pull is greatest on wet, bare, sticky soils and less on wet vegetation or on bare, sandy soils. On sticky soils, the towpaths should be left in grass or other vegetation.

Sprinkler performance will be affected by turbulence in the stream before it enters the sprinklers. Such turbulence can be caused by a variety of internal plumbing problems including protrusions in the pipe, poorly designed plumbing, changes in pipe size, elbows, and other obstacles near the base of the gun.

When moving the hose from one location to the next, a hose reel should be used. The reel should be designed so that the hose may be placed on it without first removing the pull coupler. The reel also provides a good means of storing the hose in the off-season.

Towpath Spacing.—Tests run by various researchers show that application uniformity is considerably affected by wind velocity and direction, quantity of water output, jet trajectory, type of nozzle, and operating pressure. With average wind speeds about 10 mph, CU's were 70 to 75 percent in the central portion of the fields for towpath spacings equal to 70 to 60 percent of the wetted diameters of the sprinklers.

Only the center section of a field irrigated by traveling sprinklers gets a full pass of the complete sprinkler pattern. About 400 ft on each end of most fields are not irrigated as well as the center of the field. This underirrigation can be essentially eliminated, as discussed earlier, by allowing the sprinkler to stand for a period of time at the end of the towpaths. The above CU values were based on a constant travel speed. Obviously, these values would decrease if the travel speed varied from one part of the field to another.

The continuous movement of the traveler is equivalent to having periodic-move sprinklers very closely spaced along the lateral. The effect is to improve the uniformity as compared with periodic-move gun sprinkler installations. Figure 11-49 shows a comparison between a traveling and a set gun sprinkler application pattern measured across the towpath. The traveling sprinkler produces a uniform pattern in low winds. From figure 11-49, it is evident that a towpath spacing of 80 percent of the wetted diameter would produce excellent uniformity under very calm wind conditions, whereas closer spacings would produce excessive application midway between adjacent towpaths.

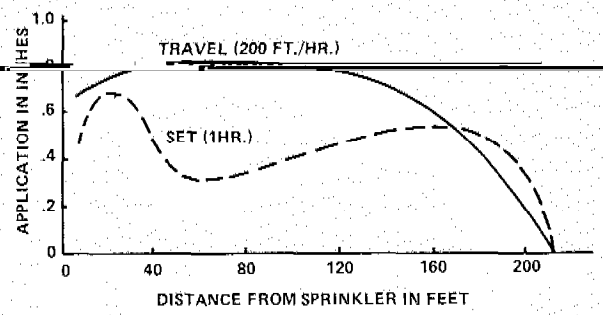


Figure 11-49.—Typical application patterns of a traveling and a set gun sprinkler operating in very low wind.

Table 11-31 gives recommended towpath spacings for 23° to 25° trajectory sprinklers as a function of wetted diameter and anticipated average wind velocities. These towpath spacings will ensure full coverage midway between towpaths. The higher percentage values should be used for tapered nozzles and the lower values for ring nozzles. Where average winds are expected to exceed 10 mph, 20° to 21° trajectory angles should be used. Where winds are negligible, 26° to 28° trajectories will give the best results.

Table 11-31. Recommended towpath spacings for traveling sprinklers with ring (lower) and tapered (higher percentages) nozzles

Sprinkler wetted diameter	Percent of wetted diameter						
	50	55	60	65	70	75	80
	Wind over 10 mph		Wind up to 10 mph		Wind up to 5 mph		No wind
ft	ft	ft	ft	ft	ft	ft	ft
200	100	110	120	130	140	150	160
250	125	137	150	162	175	187	200
300	150	165	180	195	210	225	240
350	175	192	210	227	245	262	280
400	200	220	240	260	280	300	320
450	225	248	270	292	315	338	360
500	250	275	300	325	350	375	400
550	275	302	330	358	385	412	440
600	300	330	360	390	420	—	—

Travel speed.—The travel speed should be set to traverse the length of the towpath so that there will be little down time with either one or two setups per day. Some typical travel speeds are:

1. For a 1,320-ft run such as in figure 11-9 where the traveler starts and stops at the field boundaries, the travel speed for two setups per day should be approximately 1,320/(11 × 60) = [illegible] ft/min. For one setup per day it should be between 0.9 and 1.0 ft/min.

2. For a 1,320-ft run where it is not permissible, or practical, to irrigate over the field boundaries, the sprinkler should be operated in a set position on each end of the towpath as described earlier under system layout. In each case with average sized gun sprinklers having an effective wetted diameter of 400 ft, the travel speed for one setup per day should be approximately:

$$\frac{1{,}320 \text{ ft} - 400 \text{ ft}}{60 \text{ min/hr } [23 \text{ hr} - 2(1) \text{ hr}]} \cong 0.75 \text{ ft/min}$$

This allows for a 1-hr set time, 200 ft from the field boundary at each end of the towpath. With half-hour set times and two setups per day the travel speed should be approximately 1.5 ft/min.

Application Depth.—The rate of application is unaffected by travel speed, but the depth of application is a function of speed. The average depth of water applied per irrigation by a traveling sprinkler can be computed by:

$$d = \frac{1.605\ q}{W\ S} \qquad (11\text{–}40)$$

where

d = gross depth of application (in)
q = sprinkler discharge (gpm)
W = towpath spacing (ft)
S = travel speed (ft/min)

To obtain the net depth assume an E_q between 55 and 67 percent or an E_h between 65 and 77 percent.

Rate of Irrigation Coverage.—The rate of irrigation coverage is a function of travel speed and towpath spacing. Some useful rate of coverage formulas are:

$$\text{acres covered per hour} = \frac{W\ S}{726} \qquad (11\text{–}41a)$$

$$\text{acres irrigated per 1/4-mile long run} = \frac{W}{33} \qquad (11\text{–}41b)$$

Friction Losses in Hose and Traveler.—Hose-fed traveling sprinklers must have hoses that are long (typically 660 ft), flexible, tough skinned, and capable of withstanding high pressures. High-pressure traveler hoses are made in 2.5- to 5-in diameters. They are about 5 times as expensive as pipe and often have a short life due to physical damage and difficulty of repair. Furthermore, the end pull required to drag a hose is approximately proportional to the square of the diameter. Therefore, as a rule of thumb the following relatively small diameter hoses are used for the following ranges of flow:

Hose flow rate range (gpm)	Nominal inside diameter of lay-flat hose (in)
Up to 150	2.5
100 to 300	3
250 to 600	4
400 to 750	4.5
500 to 1,000	5

The diameter of lay-flat hose increases by almost 10 percent under normal operating pressures. This gives the lay-flat hose about 20 percent more carrying capacity than the same diameter rigid plastic hose at the same friction loss gradient.

Table 11–32 gives estimated pressure losses for lay-flat hose operating at approximately 100 psi. Friction loss can be estimated by equation 23 when the actual inside hose diameter during operation is known. The more rigid thick-walled plastic hoses do not lay flat and have calibrated inside diameters that are not changed appreciably by pressure. Thus equation 23 can be used directly to estimate friction head losses for plastic hoses.

The traveler vehicle can be powered by water turbines, water pistons, or engines. In determining system pressure requirements, the pressure head loss and riser height of the traveler must be considered. This is especially true for turbine drive travelers when the pressure difference between the traveler inlet and sprinkler base typically exceeds 10 psi. Manufacturers should provide friction-loss data for their travelers operation at various flow rates and travel speeds.

Sample calculation 11–17.—System design for traveling sprinkler irrigation.

Given:

The 1/2-mile-long by 1/4-mile-wide 80-acre field with a well in the center shown in figure 11–9

Assumed irrigation efficiency of the low half: E_h = 70%

Low winds—ranging between 0 and 5 mph

Peak moisture-use rate 0.22 in/day

A corn crop to be grown on sandy soil on which the allowable application rate is 1 iph and allowable moisture depletion is 3 in.

Irrigation over the field boundaries is both permissible and practical.

Find:

The required sprinkler, nozzle, and operating pressures

The system layout

The pressure required at the hose inlet

Calculation:

The potential towpath spacings for the 2,640-ft width of the field are:

Table 11-32.—Estimated pressure head loss gradients for lay-flat irrigation hose operating at approximately 100 psi

	Nominal inside diameter (in)									
	2.5		3		4		4.5		5	
Flow rate	Pressure head loss gradient per 100 ft of hose									
gpm	psi	ft	psi	ft	psi	ft	psi	ft	psi	ft
100	1.6	3.7								
150	3.4	7.9	1.4	3.2						
200	5.6	12.9	2.4	5.5						
250			3.6	8.3	0.9	2.2				
300			5.1	11.8	1.3	3.1	0.6	1.4		
400					2.3	5.3	1.3	2.9		
500					3.5	8.1	2.1	4.8	1.1	2.5
600					4.9	11.3	2.7	6.1	1.6	3.7
700							3.6	8.2	2.1	4.9
800							4.6	10.5	2.7	6.2
900									3.4	7.9
1,000									4.2	9.7

Number of towpaths	Spacing
7	380 ft
8	330 ft
9	290 ft
10	260 ft
11	240 ft

If two travelers are used, there should be an even number of towpaths.

For the crop and soil conditions, no special consideration need be given to application rate or droplet impact.

With an E_h = 70% and a peak moisture use rate of 0.22 in/day the average gross depth of application per day during peak use periods must be:

$$d = 0.22/(70/100) = 0.32 \text{ in/day}$$

and by equation 1 the system capacity must be at least:

$$Q = \frac{453\ Ad}{fT} \qquad \textbf{(11-1)}$$

$$= \frac{453 \times 80 \times 0.32}{1 \times 23} = 504 \text{ gpm}$$

From table 11-30 a 24° gun sprinkler with a 1.4-in tapered bore nozzle will discharge 515 gpm at 80 psi and produce a 455-ft wetted diameter.

From table 11-31 the towpath spacing can be 75 percent of the wetted diameter in winds up to 5 mph. For a 455-ft wetted diameter this would be 340 ft. The nearest acceptable potential towpath spacing for the design at hand is 330 ft. Thus eight tow paths will be required as shown in figure 11-9.

It is desirable to have only one setup per day. Assuming an 8-day irrigation interval, the gross depth of water required per irrigation is 8 × 0.32 = 2.56 in. From equation 40 the required travel speed is:

$$S = \frac{1.605\ q}{W\ d} \qquad \textbf{(11-40)}$$

$$= \frac{1.605 \times 515}{330 \times 2.56} = 0.98 \text{ ft/min}$$

The time required to travel the 1,320-ft length of each towpath is:

$$\frac{1{,}320}{0.98 \times 60} = 22.5 \text{ hr}$$

This is a reasonable design. In practice the travel speed would probably be adjusted to as close to 1 ft/min as possible.

This would decrease the depth of application slightly and reduce the travel time to 22 hours.

A possible alternative is to limit the time to travel the 1,320 ft to 23 hrs by letting S = 0.96

ft/min. The required sprinkler discharge by equation 40 would then be:

$$q = \frac{2.56 \times 330 \times 0.96}{1.605} = 505 \text{ gpm}$$

This agrees with the minimum system capacity found earlier by equation 1.

An economic analysis using life-cycle costs was made assuming a hose life of 7 years and using the required sizes of travelers to drag the different sizes of hoses. The 4.5-in diameter hose proved to be the most economical size for the 515-gpm design flow rate.

From table 11-32 the estimated pressure head loss gradient for the lay-flat irrigation hose is 2.1 psi/100 ft. Using equation 23 as a basis for inter-

$$2.1 \left(\frac{515}{500} \right)^{1.75} \times \frac{660}{100} = 14.6 \text{ psi}$$

A turbine drive traveler was selected. According to the manufacturer's charts the friction plus drive turbine loss in the unit when traveling at 1 ft/min will be 7.5 psi. In addition the automatic shut-off valve has 3.5 psi loss.

The hose inlet pressure required for the traveling sprinkler is:

Sprinkler pressure	80.0 psi
Friction loss in hose	14.6
Pressure loss in traveler	7.5
Automatic shut-off valve	3.5
Riser height (10 ft)	4.3
Required hose inlet pressure	109.9 psi

System Layout

Figure 11-9 shows a typical traveling sprinkler system layout. In the design and layout of traveling sprinkler systems the following general criteria should be considered:

1. With unrestricted water supplies it is usually desirable to design the system to operate at least 20 hr per day during peak-use periods.

2. Traveling systems should normally be designed to require only one and at most two "setups" per day. (Travelers operate unattended until they reach the end of a towpath at which time the traveler and hose must be moved and set up for a new run in the next towpath.)

3. The maximum operating time should be 23 hr/day for systems requiring only one setup per day and 22 hr/day for 2 setups per day.

4. Whenever possible, systems should be designed for the traveler to begin and end at the field boundary as shown in figure 11-9. Sometimes it is not advisable or practical to irrigate over the field boundaries at the ends of the towpaths, and the sprinklers must be started 150 to 200 ft inside of the field boundaries. In such cases, a better irrigation can be applied by allowing the traveling sprinkler to stand 1 hr at each end for once-a-day setups on 1/4-mile towpaths, and 30 minutes at each end for twice a day setups. For longer towpaths this time should be increased and for shorter towpaths [illegible] towpath length.

5. If practical, where prevailing winds exceed 5 mph, towpaths should be laid out so they do not line up with the prevailing wind direction.

6. Towpaths should be laid out in the same direction as the rows, usually following the contours of steeply sloping fields.

7. The actual application rate from full circle traveling gun sprinklers ranges from about 0.3 iph for sprinklers discharging 300 gpm to 0.6 iph for 1,000 gpm units. Therefore, where infiltration is apt to be a problem, a large number of low discharge sprinklers is preferable to a few large units.

8. The width of the field should be divided by a series of integers to obtain a potential set of towpath spacings provided that irrigation outside of the field boundaries is permitted (see fig. 11-9). If it is not permissible to irrigate past the edges of the field, subtract the wetted diameter of one sprinkler from the width before dividing by the series of integers.

9. The final design layout will be a compromise between the above factors so that the number of towpaths is a multiple of the number of sprinklers; the spacing between towpaths gives reasonable uniformity under the expected wind conditions with the sprinkler nozzle size, angle of trajectory, and pressure selected; and the depth and frequency of irrigation fall within acceptable limits using one or two setups per day.

Center-Pivot Design

The main factors to be considered in the design of center-pivot irrigation systems are peak water-use-rate of the design area, system capacity, soil infiltration characteristics, sprinkler nozzle configuration, and system hydraulics. In ordinary practice, the system designer specifies the maximum required travel speed, hardware length, system discharge, nozzling configuration, pipe diameter, and perhaps the available inlet pressure. The supplier provides the center-pivot that meets the specifications. Ordinarily, the field engineer is not required to design the nozzling or any mechanical aspects of the machine.

A step-by-step general design procedure is presented in *Types of Systems* in which special consideration is given to continuous-move systems. An outline of the first six steps of the procedure, which are known as the preliminary design factors, is presented as figure 11–13.

The main advantages of center-pivot sprinkle irrigation machines are:

1. Water delivery is simplified through the use of a stationary pivot point.
2. Guidance and alignment are controlled at a fixed pivot point.
3. Relatively high water application uniformities are easily achieved with moving sprinklers.
4. After completing one irrigation, the system is at the starting point for the next irrigation.
5. Irrigation management is improved by accurate and timely application of water.
6. Accurate and timely applications of fertilizers and other chemicals can be made in the irrigation water.
7. Flexibility of operation aids in development of electric load management schemes.

These advantages eliminate the most difficult mechanical and operational problems associated with other types of self-propelled irrigation machines. Center-pivot machines, however, have some definite disadvantages. As with all irrigation machines, in order to reduce the cost per unit area irrigated, it is advantageous to irrigate as large an area as possible with a minimum amount of equipment. With center-pivot machines, this is done by irrigating as large a circle as possible since the cost of equipment is proportional to the radius, but the area irrigated is proportional to the square of the radius.

The most common radius of center-pivot machines is 1,320-ft which irrigates a 125 to 140 ac circular field depending on how far water is thrown from the end sprinklers. From an irrigation standpoint, center-pivots have the following disadvantages:

1. When the pivot point is in the center of a square field, only 125 to 132 ac of the 160-ac field will be irrigated. This leaves 20 percent of the area unirrigated unless special equipment is provided for the corners, which adds considerably to the system's cost and complexity.
2. The application rate at the outer edge of the irrigated circle will range between 1 and 8 iph depending on the nozzle configuration.
3. To reduce or eliminate runoff problems associated with these high application rates, use light, frequent applications on all but the most sandy soils or cracked clays. Thus, it may be necessary to operate faster than one revolution per day, which may not always be ideal for the crop or for the water use.
4. Since the concentric band irrigated increases with each increment of radius, most of the water must be carried toward the end of the lateral, which results in high pipe friction losses.
5. Elevation differences can be large between lateral ends that point up or down hill, resulting in wide variations in discharge.

System Capacity

The required system capacity can be computed by equation 1, as discussed in the section under *Capacity Requirement for Center Pivots*. It is often desirable to compute the unit system capacity required for different moisture use rates. If a 24-hr-per-day, 7-day-per-week operation is assumed, equation 1 can be reduced to:

$$Q = 18.9\ A\ d' \qquad \textbf{(11–42a)}$$

or

$$Q = \frac{R^2\ d'}{734} \qquad \textbf{(11–42b)}$$

where

Q = system capacity required (gpm)
A = design area (acres)
d' = daily gross depth of application required during peak moisture use rate period (in)

R = maximum radius irrigated when corner system or end sprinkler is in operation (ft)

The unit system capacity, gpm/acre, can be obtained by letting A = 1. To accommodate breakdowns, time to move the system or shutdowns to accommodate electric load management:

$$Q = \frac{453\ Ad'}{T} \qquad \textbf{(11-42c)}$$

where

T = average actual operating time (hr/day)

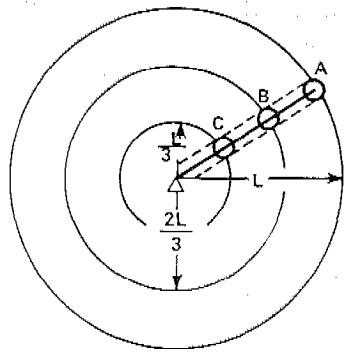
To determine the gross depth of irrigation (d) per revolution of a center pivot use equation 1.

Application Intensity

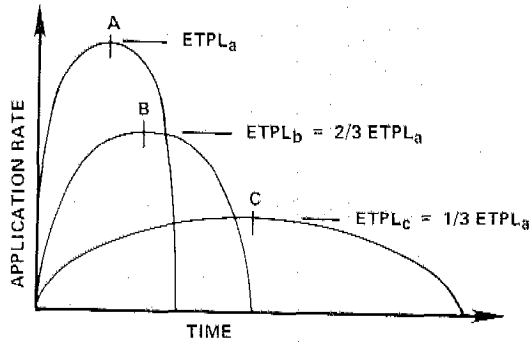
The geometrical characteristics of the center-pivot system are such that the application rate must increase with the distance from the stationary pivot point to obtain a uniform depth of application (fig. 11-50). As a result, the application rates, especially near the moving end of the lateral, often exceed the infiltration capacity of moderate- to heavy-textured soils. The resulting runoff may severely reduce the uniformity of irrigation and cause considerable loss of water, energy, and crop production.

An elliptical water application rate pattern at right angles to the moving lateral is usually assumed as in figure 11-50. A stationary water application pattern can be transformed into a moving one by dividing the pattern base width by the speed of the pivot. For the same stationary pattern and pivot speed, different moving patterns are obtained at different points along the lateral. The peak water application rate of the pattern is obtained by equating the area of the ellipse to the depth of water applied to the soil. Theoretically, the depth of water applied does not include the drift and evaporation losses; however, this is very difficult to control in practice.

Definition of ETPL.—A system parameter called ETPL can be used to simplify the analysis of field performance for transferring infiltration capacity evaluations. ETPL is the product of the "gross" peak daily water use rate (ETP) and the length of the pivot (L). A range of ETPL values from 11 to 66 ft^2/day covers most of the practical combinations



A) AERIAL VIEW OF CENTER PIVOT FIELD WITH UNIFORM WIDTH OF WETTED STRIP.



B) WATER APPLICATION RATES AT DIFFERENT POINTS ALONG PIVOT LATERAL.

Figure 11-50.—Water application rates at different points along a center pivot with uniform width of wetted strip.

of ETP and L. As an example, for ETP = 0.30 in/day and L = 1/4 mile, the value of ETPL = 33 ft^2/day. The advantage of using the parameter ETPL can be demonstrated by referring to figure 11-50. The ETPL = 33 ft^2/day at the outer edge of the pivot, ETPL = 22 ft^2/day along the circular path at 2/3 L and 11 ft^2/day at 1/3 L. If the pivot were lengthened to 1,866 ft to irrigate twice as much area, the ETPL along the outer edge would be increased to 47 ft^2/day. Thus, analyses can be made of a few ETPL values to cover the entire range of application infiltration possibilities for different positions along system laterals designed for any conceivable climate, crop, and site.

Application Rate.—Assuming that the application pattern under the sprinklers is elliptical, the average and maximum application rates at any location under the center-pivot lateral are:

$$I = \frac{2(96.3)\ r\ Q}{R^2 w} \qquad \textbf{(11–43a)}$$

and

$$I_x = \frac{4}{\pi}\ \frac{2\ (96.3)\ r\ Q}{R^2 w} \qquad \textbf{(11–43b)}$$

$$= \frac{245\ r\ Q}{R^2 w}$$

where

I = the average application rate at any point r (iph)
r = radius from pivot to point under study (ft)
I_x = the maximum application rate at any point r (iph)
Q = system capacity (gpm)
R = maximum radius irrigated by center pivot (ft)
w = wetted width of water pattern (ft)

nomenon. For example, in figure 11–51 the shaded portion depicts the potential runoff. If the system were speeded up, the peak of the application pattern would remain the same but the breadth (time) would decrease. This would decrease or even eliminate the potential runoff.

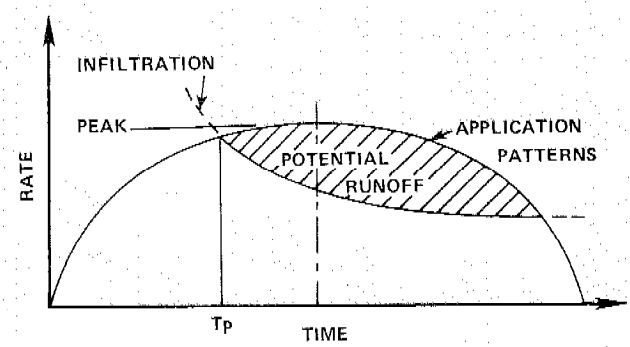


Figure 11–51.—Intersection between a typical elliptical pattern of water application rate under a center pivot and a potential infiltration curve.

When field experience is not available for center-

and irrigation demand factors and independent of the travel speed.

Infiltration Rate.—General soil infiltration characteristics for sprinkler systems are presented in table 11–4. The table values can often be increased by over 100 percent when applying light, daily irrigations with a center-pivot system.

Surface storage is important in minimizing runoff from center-pivot systems. For example, assume daily irrigations of d′ = 0.30 in are applied and 0.1 in can be stored on the surface. Then only 0.2 in must be infiltrated while the system is overhead to prevent runoff. Potential values of surface storage are:

Slope (%)	Potential surface storage (in)
0–1	0.5
1–3	0.3
3–5	0.1

Pitting or diking implements can be used to increase surface storage.

Soil infiltration capacity decreases with time, which allows center-pivots to apply higher applications rates without runoff. Light, frequent applications take maximum advantage of this phe-

figure 11–52 can be used as a guide to identifying potential runoff problems. In general, soils above the 0.3 iph contour are questionable for center-pivot irrigation; soils lying between the 0.3- and 0.5-iph contour require careful design and management, and soils below the 0.5-iph contour are ideal for center-pivot irrigation. Additional and somewhat contradictory criteria are shown by the dotted lines. Obviously, figure 11–52 should only be used as a "first approximation" since factors other than soil texture affect the infiltration capacity of soils. Field trials may be needed to determine intake rates for center-pivot design.

Surface Sealing.—Field observations show that the surface seal or crust is important in the performance of the system. The soil seal is a thin compacted layer between 5 and 30 mm thick, which is less permeable to water than the underlying layers. The two major factors involved in rearrangement of particles near the soil surface and development of the seal are surface puddling coupled with raindrop impact. These two factors rearrange the surface particles and cause vertical erosion. Numerous studies have been conducted to investigate the problem of raindrop impact energy and soil surface sealing in relation to infiltration and runoff; how-

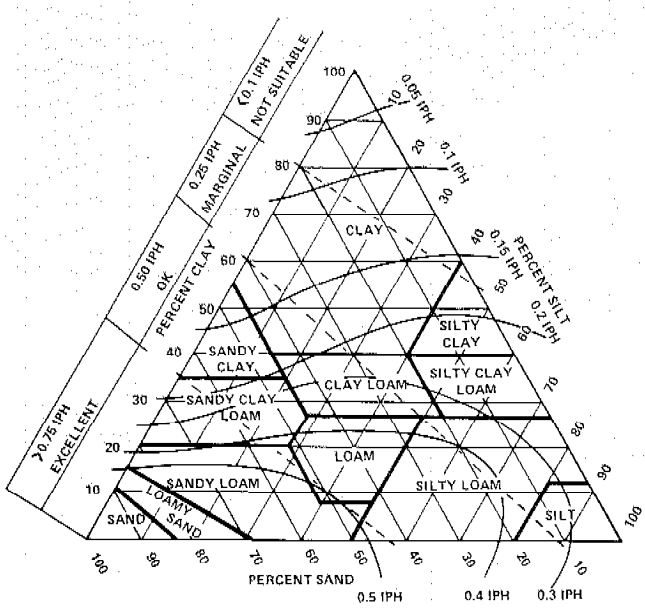


Figure 11-52.—Soil triangle showing proportions of sand, silt, and clay for different soil textures plus general infiltration rate contours.

ever, no satisfactory quantitative relation has been established.

The hydraulic permeability of the soil surface seal is a function of drop size (fig. 11-16). Larger raindrops travel farther because of their greater mass and velocity. As a result, drop size increases with the distance from the sprinkler. With impact sprinklers, a wider pattern is usually obtained by using sprinklers with relatively larger nozzle sizes operating at relatively higher pressures. Therefore, the water spectrum of such a pattern is usually made up of larger drops than are found in narrow patterns (fig. 11-15.) For a given nozzle size, a change in pressure would affect the drop-size distribution and the wetted diameter. Generally, as pressure increases, drop size decreases. Beyond a certain recommended operating pressure, however, the wetted radius or distance of throw also decreases as a result of the excessive reduction in drop sizes. Narrow patterns produced by a spray nozzle arrangement are usually made up of very small drops.

The ultimate consequence of raindrop impact is that the wetted radius produced by a sprinkler can be used as an index to the average size of the drops produced by it. Therefore, the detrimental effect of the falling raindrops on the hydraulic permeability of the soil surface and the formation of the soil surface seal can be related to the wetted radius of the sprinkler pattern. High instantaneous application rates also contribute to sealing. As a rule instantaneous rates increase proportionately with wetted radius unless pressures are abnormally high or low.

Various soils show different degrees of aggregate breakdown and surface sealing under falling raindrops. With coarse-textured soils such as sands, surface sealing is usually not a problem because of good structural stability and the absence of very fine particles. However, surface sealing is often a problem on medium- and fine-textured soils with weak structures. Such soils are apt to collapse and settle and have vertical erosion of fine particles.

Sprinkler-Nozzle Configuration

The sprinkler-nozzle configuration used for most center-pivot laterals is one of the following:

1. *Uniform spacing* of 30 to 40 ft between sprinklers, with the discharge increasing in proportion to the distance from the pivot (fig. 11-53).
2. *Uniform sprinkler discharge*, with the distance between sprinklers decreasing from 30 ft near the pivot to 5 ft in inverse proportion to the distance from the pivot.
3. A *combination* of (1) and (2).

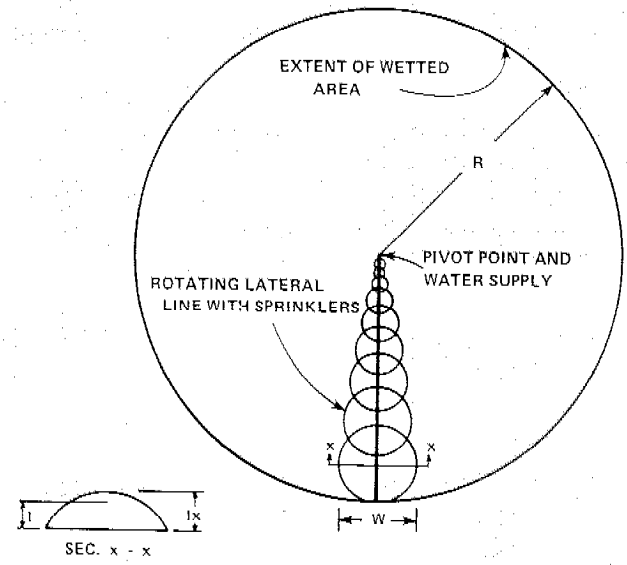


Figure 11-53.—Watering characteristics of center-pivot irrigation machines.

Uniform spacing between outlets is most commonly used for simplicity of manufacture and ease of field assembly; however, when uniform sprinkler spacings are used, relatively large nozzles and high pressures are required. The high pressures result in high energy costs, and on delicate soils without cover the droplets from the large nozzles may cause crusting and surface sealing.

To avoid the problems associated with the use of large nozzles, combination spacings are often used. A typical combination spacing strategy is to use a 40-ft sprinkler spacing along the first third of the lateral, a 20-ft spacing along the middle third and a 10-ft spacing along the last third of the lateral. Thus, the outlets can be uniformly spaced at 10-ft intervals along the lateral. To vary the sprinkler spacing merely close off some of the outlets with pipe plugs. Thus, sprinklers are installed in every fourth outlet along the first third of the lateral, every other outlet along the middle third, and every outlet along the last third of the lateral.

The general strategy for selecting the nozzle sizes along a center-pivot lateral is to:

1. Determine the discharge required from each sprinkler to apply a uniform application of water throughout the irrigated area.
2. Then, starting with a design pressure at either end determine the pressure available at each sprinkler outlet.
3. From the required discharge and available pressure, select the appropriate nozzle size in accordance with equation 12.

Sprinkler Discharge.—The sprinkler discharge required at any outlet along a center-pivot lateral can be computed by:

$$q_r = r\, S_r \frac{2Q}{R^2} \qquad \textbf{(11-44)}$$

where

q_r = sprinkler discharge required at r (gpm)
r = radius from pivot to outlet under study (ft)
S_r = sprinkler spacing at r (which is equal to half the distance to the next upstream sprinkler plus half the distance to the next downstream sprinkler) (ft)
Q = system capacity (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

Sprinkler Configurations.—The pressures and wetted widths produced by the sprinkler configurations commonly used on center-pivot laterals are presented in table 11-33. Impact sprinklers operating at the low end of the pressure range produce large droplets that may cause excessive soil sealing. "Breakup pins" can be used to remedy this, but the pins reduce the wetted width of the patterns about 25 percent.

Table 11-33.—Nozzle pressure and pattern width range for various center-pivot sprinkler configurations

Type	Pressure range (psi)	Pattern width range[1] (ft)
Fixed spray nozzles[2]	15-30	20-45
Uniform discharge with rotating sprinklers	20-55	75-90
Combination spacing with rotating sprinklers	25-60	80-110
Uniform spacing with rotating sprinklers	60-90	150-175

[1] At outer end of radius.
[2] All nozzle spacing arrangements.

The fixed spacing nozzles produce narrow pattern widths and consequent high application rates (see eq. 43). Thus their use is limited to high infiltration soils or to nearly level fields with good potential for surface water storage. Spray nozzles produce small drops that do not cause surface sealing but are subject to high wind drift losses. Some fixed spray nozzles, however, are available that produce coarser sprays to reduce wind drift problems. While low pressure is an advantage of fixed spray nozzles in terms of energy use, it will cause water distribution problems because of sensitivity to pressure changes resulting from lateral rotation over uneven topography.

The large nozzles used for uniform spacing produce a wide pattern and coarse drops. The wide pattern gives a relatively low application rate, but due to drop impact, surface sealing reduces the soil infiltration capacity and runoff becomes a problem on many soil types.

The combination spacing with rotating sprinklers is perhaps the best compromise for most soils.

Where soil sealing and infiltration rate are likely to be problems, relatively low pressures can be used to save energy. For soils that are more difficult to manage, higher pressures should be used. On undulating topography, where pressures vary because of elevation changes, flexible orifice nozzles can be used to maintain the desired discharge.

Angle of Trajectory.—Rotating sprinklers with various angles of trajectory are available for use on center-pivot laterals. High trajectory (23° to 27°) sprinklers normally used for periodic-move and fixed systems often result in excessive drift losses when placed high above the ground along center-pivot laterals. Trajectory angles of center-pivot sprinklers recommended to minimize drift losses range between 6° and 18°, with the low end of the range being preferable in high winds. Table 11-34 shows drift losses obtained from some typical field can test data for center pivots with different nozzle configurations. An analysis of the data in the table gives the following averages: low angle has 12 percent loss in 10-mph wind, spray has 17 percent loss in 6-mph wind, and high angle has 29 percent loss in 10-mph wind.

End-Gun Operation.—The designer can compute the capacity of the end gun sprinkler (q_g) by equation 44 letting S_r equal 90 percent of the radius wetted by the end gun and r equal the lateral pipe length (L) plus $S_r/2$.

Table 11-34.—Drift losses from field evaluations of center pivots with different nozzle configurations

Nozzle configuration	Trajectory angle	Wind (mph)	Temperature (°F)	Drift loss (%)
Spray	—	3	80	20
Combination	6°	7	80	15
Combination	6°	7	88	10
Combination	23°	7	90	18
Spray	—	9	95	25
Combination	6°	10	86	3
Uniform discharge	6°	10	88	17
Combination	6°	12	86	7
Combination	low	4	83	6
Spray	—	6	90	14
Spray	—	8	92	10
Uniform spacing	high	8	86	41
Uniform spacing	high	9	86	13
Combination	low	12	90	19
Uniform spacing	high	13	91	36
Uniform spacing	high	13	92	39
Uniform discharge	low	16	91	16

Part-circle sprinklers should be used and the angle should be set as shown in figure 11-54 for the best coverage on most systems.

Large end-gun sprinklers can add significantly to the area irrigated by a center pivot. For example, by adding an additional 100 ft of radius to a 1,320-ft system the area covered will be increased from 125 to 145 ac; however, where end guns are used only in the field corners, the effect of the on-off operation must be considered. If the gun discharge exceeds 20 percent of the normal system discharge, the effect on the quality of irrigation on the larger inner field area should be carefully considered. Some of the other problems are that water distribution from end guns is often severely affected by wind, booster pumps are required on all of the lower pressure nozzling configurations, and the high application intensity that is typically found under end guns may be detrimental to the soil tilth and crop.

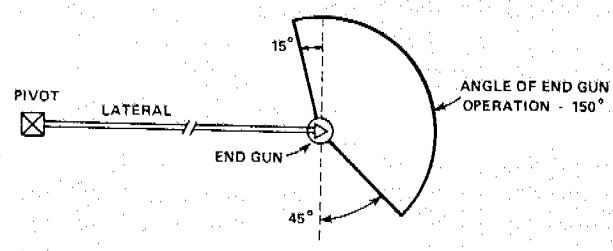


Figure 11-54.—Top view of end-gun sprinkler wetting pattern showing recommended angle of operation.

Lateral Hydraulics

The discharge per unit length of lateral increases linearly along center-pivot laterals as described by equation 44. Therefore, the hydraulic characteristics of center-pivot laterals are different than for periodic-move or linearly moving sprinkler laterals that were discussed earlier.

Lateral Flow Rate.—The flow rate at any point along a center-pivot lateral can be computed by:

$$Q_r = Q\left(1 - \frac{r^2}{R^2}\right) \qquad (11\text{-}45)$$

where

Q_r = lateral flow rate at r (gpm)
r = radius from pivot to point under study (ft)

Q = system capacity (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

The end-gun flow rate can be computed by setting r equal to the length of the lateral pipe (L) and R equal to L plus 90 percent of the radius wetted by the end gun to obtain:

$$q_g = Q\,(1 - \frac{L^2}{R^2}) \qquad \textbf{(11–46)}$$

where

q_g = the end gun discharge (gpm)
L = the length of the lateral pipe (ft)

(An alternative method for computing end gun discharge using equation 44 is described above.)

Lateral Friction Loss.—The pipe friction loss for a center-pivot lateral can be computed by combining equations 16 and 17 to obtain:

$$(H_f)_{cp} = 10.50\ F\ R\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$$

The reduction coefficient is F = 0.543 for center-pivot laterals that have a large number of uniformly increasing discharges per unit length, therefore:

$$(H_f)_{cp} = 5.7\ L\ (\frac{Q}{C})^{1.852}\ D^{-4.87} \qquad \textbf{(11–47)}$$

where

$(H_f)_{cp}$ = the pipe friction loss in the center-pivot lateral (ft)
L = the length of the lateral pipe that must be equal to the maximum radius wetted by the center pivot (ft)
Q = inlet flow rate or system capacity (gpm)
C = the friction coefficient that usually is taken as 130 for galvanized steel and 145 for epoxy-coated steel
D = inside diameter of the pipe (in)

Equation 47 assumes that there is uniformly increasing discharge per unit length along the pipe; thus, when a very large gun sprinkler is installed on the moving end, special adjustments must be made. For ordinary end guns, however, the effectively irrigated radius (R) can be substituted for L in equation 47 to compute $(H_f)_{cp}$. To compute the pipe friction loss in systems with very large end-gun volumes in proportion to the volume of water for the rest of the system so that L is considerably less than the maximum radius (R) effectively irrigated by the center pivot, $(H_f)_{cp}$ can be computed as follows:

1. Determine $(H_f)_R$ by letting L = R in equation 47.
2. Determine $(H_f)_{R-L}$ by letting: $Q = q_g$, and $L = r_g$ where r_g is the radius from the pivot to the end gun, i.e., L = R − L
3. Then:

$$(H_f)_{cp} = (H_f)_R - (H_f)_{R-L} \qquad \textbf{(11–48a)}$$

The above procedure can be expressed in a single formula for systems with end guns as:

$$(H_f)_{cpg} = 5.7\ R'\ (\frac{Q}{C})^{1.852}\ D^{-4.87} \qquad \textbf{(11–48b)}$$

where

$$R' = R - [(R - L)\,(1 - \frac{L^2}{R^2})^{1.852}]$$

Economic Pipe Sizes.—Center-pivot lateral pipe should be sized according to the economic selection procedures described under *Life Cycle Costs.* The sum of annual fixed costs plus fuel costs should be minimized. Since the flow rate (Q_r) in the pipe decreases as the radius from the pivot (r) increases (eq. 45) it is often profitable to use multiple pipe-size laterals. Smaller pipes not only save on material costs, but the span length for smaller pipes can often be increased, resulting in further savings on the supporting drive units.

The best trade-off between fixed and operating costs can be based on a unit-length analysis as described in sample calculation 11–13. If several center-pivot systems are designed using the same economic and hydraulic parameters, a chart such as figure 11–38 can be developed for the selection of center-pivot pipe using economic parameters.

When more than one pipe size is used for a center-pivot lateral a procedure similar to the one leading to equation 22 for laterals with two pipe sizes should be used. The main point to keep in mind is that equation 47 assumes that discharge increases uniformly per unit length along the pipe so that there is no flow past the section under study.

Thus, to compute the $(H_f)_{cp}$ with two or more pipe sizes all friction loss computations must be made with lengths of pipe that include the distal end. Furthermore, for systems with end guns, the distal end is at the limit of the radius effectively irrigated. The conceptual difference between equation 48b and equation 22 is that there is no pipe and consequently no pipe friction loss past the end gun in the latter equation.

Application Uniformity and Depth.—Very high DU and CU values should be obtained from center pivots that are properly nozzled and where pressure variations due to topographic effects are not significant. Under high winds, an individual pass of the lateral may not produce a good uniformity, but the sum of multiple passes should. To ensure better seasonal uniformity, the pivot speed should be set to require approximately 6 hours more or less than a full number of days per revolution, i.e., 18, 30, 42, 54 hr, etc. This will ensure that the pivot experiences different wind conditions as the lateral passes over a given site from one irrigation to the next.

To determine the travel speed of the end-drive unit for a given number of hours per rotation:

$$v = \frac{2\,\pi\,L'}{60\,f\,T} \qquad \textbf{(11-49)}$$

where

v = the travel speed of the end drive unit (ft/s)
L' = length from the pivot to the last drive unit (if there is an overhang, L' will be less than the pipe length) (ft)
f = time allowed for completion of one irrigation (days)
T = actual operating time (hr/day)

As mentioned earlier, the gross depth of application can be determined by equation 1.

Pressure changes due to elevation differences in the field adversely affect uniformity and system flow rate especially where low-pressure nozzling is used. To compensate for topographic effects, flow control devices such as flexible orifice nozzles can be used at each sprinkler; the system can be speeded up when pointing downhill and slowed down when pointing uphill, or the inlet pressure can be decreased when the lateral is pointing downhill and increased when it is pointing uphill.

The center-pivot lateral acts as one giant sprinkler, and the general relationship between discharge and inlet pressure can be approximated by:

$$Q_2 = K_{cp}\sqrt{P_{cp2}} = Q_1\left(\frac{P_{cp2}}{P_{cp1}}\right)^{1/2} \qquad \textbf{(11-50)}$$

where

Q = system discharge (gpm)
K_{cp} = the discharge coefficient of the system
P_{cp} = the lateral pipe inlet pressure measured at the top of the pivot point (psi or ft)

The value of K_{cp} can be computed letting Q and P_{cp} be the design values in equation 50.

Sample calculation 11-18.—Center-pivot lateral design.

Given:
A center-pivot lateral with the following specifications:
- Length: L = 1,300 ft, L′ = 1,260 ft to end drive unit
- Pipe: galvanized 6-5/8-in 10 gauge steel with C = 130 and D = 6.36 in
- Wetted area: The desired maximum irrigated radius when the end gun is in operation, R = 1,400 ft
- Capacity: Sufficient to apply a gross of d″ = 0.30 in/day when operating an average of 22 hr/day
- Nozzling: Combination spacing of rotating sprinklers with a minimum pressure of 45 psi at the end of the lateral.

Find:
- The system capacity, Q
- The discharge of a sprinkler at r = 1,200 ft from the pivot where the sprinkler spacing, S_r = 10 ft
- The average application rate 1,200 ft from the pivot, I
- The lateral flow rate at r = 1,200 ft
- The required discharge rate of the end gun, q_g
- The pipe friction loss, $(H_f)_{cp}$
- The end drive unit travel speed for making a lateral rotation every 66 hours of continuous operation
- The depth of application with a 66-hr cycle time

Calculations:

The area irrigated, assuming the end-gun sprinkler is always on, is:

$$A = \frac{\pi\ 1400^2}{43560} = 141.4 \text{ ac}$$

By equation 42c the system capacity should be:

$$Q = \frac{453\ Ad'}{T}$$

$$= \frac{453 \times 141.4 \times 0.30}{22} = 873 \text{ gpm}$$

The discharge of a sprinkler at r = 1,200 ft can be determined by equation 44 as:

$$q_r = r\ S_r\ \frac{2\ Q}{R^2}$$

$$= \frac{1200 \times 10 \times 2 \times 873}{(1400)^2} = 10.7 \text{ gpm}$$

Interpolating from table 11–13 this would require a nozzle slightly larger than 7/32 in operating at 45 psi with w ≅ 107 ft.

The average application rate at r = 1,200 ft by equation 43a is:

$$I = \frac{2\ (96.3)\ r\ Q}{R^2\ w}$$

$$= \frac{2(96.3) \times 1200 \times 873}{(1400)^2 \times 107} = 0.96 \text{ iph}$$

The lateral flow rate past r = 1,200 ft is computed by equation 45 as:

$$Q_r = Q\ (1 - \frac{r^2}{R^2})$$

$$= 873\ (1 - \frac{(1200)^2}{(1400)^2}) = 232 \text{ gpm}$$

The required end-gun discharge is computed by equation 46 as:

$$q_g = Q\ (1 - \frac{L^2}{R^2})$$

$$= 873\ (1 - \frac{(1300)^2}{(1400)^2}) = 120 \text{ gpm}$$

The pipe friction loss can be computed directly by equation 48b or in a three-step process by equation 47 and 48a. The three step process starting with equation 47 gives:

$$(H_f)_R = 5.7\ R\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$$

$$= 5.7 \times 1400\ (\frac{873}{130})^{1.852}\ (6.36)^{-4.87}$$

$$= 33.2 \text{ ft}$$

and

$$(H_f)_{R-L} = 5.7 \times 100\ (\frac{120}{130})^{1.852}\ (6.36)^{-4.87}$$
$$= 0.1 \text{ ft}$$

Therefore, by equation 48a

$$(H_f)_{cp} = (H_f)_R - (H_f)_{R-L}$$
$$= 33.2 - 0.1 = 33.1 \text{ ft}$$

The above computations point out that $(H_f)_{cp}$ can be computed directly by substituting R for L in equation 47 for end guns where $q_g < 1/4Q$. This is demonstrated by the insignificance of the computed $(H_f)_{R-L} = 0.1$ ft as compared to $(H_f)_{cp} = 33.1$ ft.

The speed at which the end drive unit must travel to complete a cycle in 66 hours can be determined by equation 49 as:

$$v = \frac{2\ \pi\ L'}{60\ fT}$$

$$= \frac{2\ \pi\ 1260}{60 \times 66} = 2.0 \text{ ft/min}$$

The gross depth of application with a 66-hr cycle time by equation 1 is:

$$d = \frac{Q\ f\ T}{453\ A}$$

$$= \frac{873 \times 66}{453 \times 141.44} = 0.90 \text{ in}$$

And the net depth of application assuming E_q =

$$80\% \text{ is: net depth/irrigation} = \frac{E_q\, d}{100}$$

$$= \frac{80 \times 0.90}{100}$$

$$= 0.72 \text{ in}$$

Operating Pressures

The minimum pressure, inlet pressure, and end-gun pressures for center-pivot systems should all be examined.

Minimum Pressure.—The minimum pressure will normally occur at the end of the lateral when it is pointing uphill. The minimum pressure should be set according to the sprinkler-nozzle configuration to avoid producing a watering pattern that will [redacted] minimum recommended operating pressures that are available for the various sprinkle-nozzle configurations should be followed.

Inlet Pressure.—The inlet pressure required at the base of the pivot point is equal to the sum of the following pressure heads, elevation differences, and friction losses:

1. Minimum sprinkler pressure.
2. Elevation difference between the pivot and the end of the lateral when it is pointing uphill. When the pivot is at the high point of the field the elevation difference will be negative. In rolling fields use the elevation difference between the pivot and the highest point in the field.
3. Height of the pivot lateral above the ground.
4. Friction loss in lateral pipe plus 10 percent to cover miscellaneous losses.
5. Friction loss in on-off and flow control valves. When several pivots are operated from the same pumping plant, an automatic valve should be provided to shut the water off at the pivot in case of a mechanical breakdown. For center pivots supplied directly from a well, the pump itself can be shut down; therefore, a valve is unnecessary. End guns may also need to be shut on and off to water the corners without wetting roadways running along the field.

End-Gun Pressure.—End-gun pressures should be at least 50 psi and preferably above 65 psi for good irrigation. The recommended pressure depends on nozzle size and type as well as on soil, crop, and wind characteristics. Booster pumps can be mounted on the last drive unit to provide the necessary pressure.

Elevation-Discharge Relationship

When a center-pivot system is used on a sloping field the sprinkler pressures vary as the lateral rotates. Typical nozzling configurations are designed to give uniform water application when the lateral is on a contour, but pressure or flow control devices are not usually provided. Thus, when the lateral is pointing uphill the individual sprinkler discharges drop causing the system discharges to decrease, and when pointing downhill the discharges increase.

Discharge Variations.—The variation in discharge caused by elevation differences is a function of the nozzle discharge coefficients and pipe friction loss characteristics. To simplify estimating the system discharge when the lateral is on a uniform [redacted] be represented by a weighted average elevation location for the entire lateral:

$$R_w = \frac{L}{3Q}(2Q + q_g) \qquad \textbf{(11–51a)}$$

which can also be computed by:

$$R_w = \frac{2L}{3} + \frac{L}{3}\left(1 - \frac{L^2}{R^2}\right) \qquad \textbf{(11–51b)}$$

where

R_w = radius from the pivot to the location of the weighted average elevation (ft)
L = the length of the lateral pipe (ft)
Q = system capacity (gpm)
q_g = the end gun discharge (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

To estimate the overall effect of elevation changes, the sprinklers along the lateral can be thought of as all being at R_w. The pressure head changes as the lateral rotates will then be (± slope) × R_w. From this the variations in Q can be computed by equation 50 as demonstrated in sample calculation 11–19.

Variations in discharge are not uniform and obviously become greater as one moves away from the pivot point. This reduces the application uniformity

and even where Q may be sufficient in the uphill position, underirrigation may occur at the end of the lateral. One method for reducing the uneven watering resulting from elevation-induced flow rate changes is to slow the lateral rotation when it is in the uphill position and speed it up when in the downhill position. Another possibility besides pressure or flow regulation for each sprinkler, is to increase and decrease the pivot inlet pressure when pointing uphill and downhill, respectively.

When center-pivots are fed directly from wells, or individual pumping plants, the changes in Q will be further modified by the well and pump characteristics. Therefore, a plot should be made to determine where the uphill and downhill system curves intersect the pump curve to accurately determine the expected variations in Q.

Sample calculation 11-19. Pivot inlet pressure and end-gun booster pump design.

Given:

The pivot information from sample calculation 11-18

The field has a uniform 2 percent slope

The lateral is 10 ft above the ground

Find:

The inlet pressure required at the base of the pivot

The booster pump horsepower required to provide a gun pressure of 65 psi

The system discharges when the lateral is pointing uphill and downhill assuming the system is designed for Q = 873 gpm when the lateral is on the contour

Calculations:

The inlet pressure at the base of the pivot should be:

Minimum nozzle pressure (45 psi)	= 104.0 ft
Elevation difference (1,300 × 2%)	= 26.0
Height of pivot lateral	= 10.0
Friction loss in pipe[1]	= 33.1
Plus 10% minor loss	= 3.3
Inlet valve loss (3.5 psi)	= 8.0
Required inlet pressure	= 184.4 = 80 psi

[1] *This is quite high and an economic analysis might indicate the use of larger pipe.*

To operate the end gun at 65 psi and to take care of valve and plumbing friction losses (5 psi), the pressure of the end of the lateral should be boosted by:

$$45 \text{ to } 70 = 25 \text{ psi} = 58 \text{ ft}$$

The horsepower required for a 65 percent efficient booster pump can be computed by equation 36 as:

$$BHP = \frac{q_g \times H}{3960\ E_p/100}$$

$$= \frac{120 \times 58}{3960 \times 65/100} = 2.7 \text{ hp}$$

[illegible]

constant is computed by equation 50. The average nozzle pressure variation can be approximated by the elevation changes at the weighted average elevation radius (R_w). The R_w can be determined by equation 51a:

$$R_w = \frac{L}{3Q}(2Q + q_g)$$

$$= \frac{1300}{3(873)}[\,2(873) + 120\,]$$

$$= 926 \text{ ft}$$

The elevation 926 ft from the pivot will vary ± 0.02 × 926 = 18.5 ft.

If the lateral was designed for Q = 873 gpm at an inlet pressure of 184.4 ft, the flow variation can be computed by equation 50 as follows: First subtract the height of the pivot since this does not vary with flow and compute K_{cp} as:

$$K_{cp} = \frac{Q}{\sqrt{P_{cp}}} = \frac{873}{\sqrt{184.4 - 10}} = 66.1$$

Then compute Q when the lateral points uphill:

$$(Q)up = 66.1\sqrt{184.4 - 10 - 18.5} = 825 \text{ gpm}$$

And when the lateral is downhill:

$$(Q)dn = 66.1\sqrt{184.4 - 10 + 18.5} = 918 \text{ gpm}$$

Machine Selection

Ultimately the type, power and speed of drive system, type of pipe and protective coating, span length, lateral height, type of end gun or corner system, wheel or tire size, and supplier must be selected by the user. Local field experience and availability of service should be considered as well as cost.

Some considerations as to machine suitability are:

For the application of chemicals, a drive system capable of providing a fast rotation speed is needed.

On undulating terrain, span length may need to be adjusted to keep the lateral from scraping the crop or ground.

On unstable soils, high flotation tires may be required.

For steep and undulating terrain, heavy duty drive systems are needed. Some waters may cause corrosion in galvanized pipe. In such instances, epoxy-coated pipe and structures are recommended.

Field Test Data

It is good practice to occasionally test the performance of a center-pivot system to check the uniformity of application and flow characteristics.

Information Required.—Center-pivot systems are propelled by using diverted water or such independent power sources as electricity, oil hydraulics, or compressed air to move the lateral. If water is used, it must be included as part of the total water applied; this somewhat lowers computed values of water use efficiency. When the water discharging from the pistons or turbines is distributed as an integral part of the irrigation pattern, its effectiveness should be included in DU; otherwise, it should be ignored in the DU computations but should be included in computing E_q.

The procedures and logic are similar for evaluating all types of sprinkle systems. Effective use of procedures given in this section will depend on a good understanding of the procedures described in the section on testing periodic-move and fixed systems.

The following information is required for evaluating center-pivot irrigation systems.

1. Rate of flow for the total system.
2. Rate of flow required to propel the system if it is water driven.
3. Depth of water caught in a radial row of catch containers.
4. Travel speed of end-drive unit.
5. Lateral length to end-drive unit and radius of the portion of the field irrigated by the center pivot.
6. Width of the wetted strip at end-drive unit.
7. Operating pressure and diameter of largest sprinkler nozzles at the end of the lateral.
8. Approximate differences in elevation between the pivot and the high and low points in the field and along the lateral at the test position radius.
9. Additional data indicated on figure 11-55.

Accurate measurement of the flow rate into the system is needed for determining the E_q of the system; however, if no accurate flow metering device is at the inlet, the E_q can only be estimated.

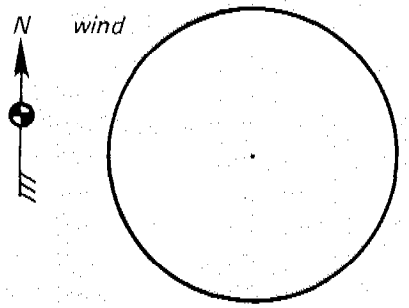
Equipment Needed.—The equipment needed is essentially the same as for the full evaluation of rectangular sprinkler-lateral systems.

1. A pressure gauge (0–100 psi) with pitot attachment (fig. 11-44).
2. A stopwatch or watch with an easily visible second hand.
3. From 60 to 100 (depending on the lateral length) catch containers such as 1-quart oil cans or plastic freezer cartons.
4. A 250-ml graduated cylinder to measure volume of water caught in the containers.
5. A tape for measuring distances in laying out the container row and estimating the machine's speed.
6. A soil probe or auger.
7. A hand level and level rod to check differences in elevation.
8. A shovel for smoothing areas in which to set catch containers and for checking profiles of soil, root, and water penetration.
9. Figure 11-55 for recording data.
10. Manufacturer's nozzle specifications giving discharge and pressure and the instructions for setting machine's speed.
11. For water-driven machines which do not incorporate the drive water into the sprinkler patterns, a 2- to 5-gal bucket and possibly a short section of flexible hose to facilitate measuring the drive water discharge.

Field procedure.—Fill in the data blanks of figure 11-55 while conducting the field procedure. In a field having a low-growing crop or no crop, test the system when the lateral is in the position at which the differences in elevation are least. In tall-growing crops, such as corn, test the system where the lateral crosses the access road to the pivot point.

1. Location _____, observer _____, date & time _____
2. Equipment: make _____, length ____ ft, pipe diameter ____ in
3. Drive: type _____ speed setting ____ %, water distributed? ____

4. Irrigated area = $\frac{3.14\ (\text{wetted radius} \_\_\_\_\_\ \text{ft})^2}{43{,}560}$ = _____ acres

5. 

*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind _____ mph, temperature _____ °F

Pressure: at pivot _____ psi

at nozzle end _____ psi

Diameter of largest nozzle _____ in

Comments: _____

6. Crop: condition _____, root depth ____ ft
7. Soil: texture _____, tilth _____, avail. moisture ____ in/ft
8. SMD: near pivot ____ in, at 3/4 point ____ in, at end _____ in
9. Surface runoff conditions at 3/4 point ____, and at end _____
10. Speed of outer drive unit _____ ft per _____ min = _____ ft/min

11. Time per revolution = $\frac{(\text{outer drive unit radius} \_\_\_\_\ \text{ft})}{9.55\ (\text{speed} \_\_\_\_\_\ \text{ft/min})}$ = _____ hr

12. Outer end: water pattern width _____ ft, watering time ____ min
13. Discharge from end drive motor _____ gal per _____ min = _____ gpm
14. System flow meter _____ gallons per _____ min = _____ gpm
15. Average weighted catches:

System = $\frac{(\text{sum all weighted catches} \_\_\_\_\_)}{(\text{sum all used position numbers} \_\_\_\_)}$ = _____ ml = _____ in

Low 1/4 = $\frac{(\text{sum low 1/4 weighted catches} \_\_\_\_\_)}{(\text{sum low 1/4 position numbers} \_\_\_\_)}$ = _____ ml = _____ in

16. Minimum daily (average daily weighted low 1/4) catch:

$\frac{(\_\_\_\_\ \text{hrs operation/day}) \times (\text{low 1/4 catch} \_\_\_\_\ \text{in})}{(\_\_\_\_\_\ \text{hrs/revolution})}$ = _____ in/day

17. Container catch data in units of _____, volume/depth _____ ml/in

Span length _____ ft, container spacing _____ ft

Evaporation: initial ____ ml ____ ml

final ____ ml ____ ml

loss ____ ml ____ ml, ave ____ ml = ____ in

Figure 55.—Center pivot sprinkle irrigation evaluation.

Span No.	Container			Span No.	Container		
	Position number	× Catch =	Weighted catch		Position number	× Catch =	Weighted catch
	1				37		
	2				38		
	3				39		
	4				40		
	5				41		
	6				42		
	7				43		
	8				44		
	9				45		
	10				46		
	11				47		
	12				48		
	13				49		
	14				50		
	15				51		
	16				52		
	17				53		
	18				54		
	19				55		
	20				56		
	21				57		
	22				58		
	23				59		
	24				60		
	25				61		
	26				62		
	27				63		
	28				64		
	29				65		
	30				66		
	31				67		
	32				68		
	33				69		
	34				70		
	35				71		
	36				72		

Sum all: used position numbers _____, weighted catches _____

Sum low 1/4: position numbers _____, weighted catches _____

Figure 11-55.—Center pivot sprinkle irrigation evaluation (Cont.).

1. Set out the catch containers along a radial path beginning at the pivot, with a convenient spacing no wider than 30 ft; a 15- or 20-ft spacing is preferable. The radial path does not need to be a straight line. Convenient spacings can be obtained by dividing the span length by a whole number such as 3, 4, 5, 6, etc. For example, if the span length is 90 ft, use a 30-ft or 22.5-ft spacing. This simplifies the catchment layout since measurements can be made from each wheel track and the spacing related to the span, i.e., 4th span + 50 ft. Obviously, containers should not be placed in wheel tracks or where they would pick up waste exhaust water from water-driven systems in which the exhaust is not distributed. When exhaust water is incorporated into the wetting pattern, lay out containers so they will catch representative samples of the drive water.

As an example, a typical layout between wheel tracks for 90-ft spans and any type of drive would be:

a. Place the first container 5 ft downstream from the pivot.

b. Set containers 2, 3, and 4 at 22.5-ft intervals. The fourth container is now 17.5 ft from the wheel track of the first span.

c. Repeat the above procedure to the end of the actual wetted circle.

To save time it may be convenient to leave out the first few containers adjacent to the pivot since the watering cycle is so long in this area. Frequently, the containers under the first one or two spans are omitted with little adverse effect on the evaluation. A number should be assigned to each container position with a sequential numbering system beginning with 1 at the container position nearest the pivot point. Even the locations not having containers under the first spans should be numbered.

2. Fill in the blanks in parts 1 through 9 dealing with climatic and soil moisture conditions, crop performance, topography and general system, and machine and test specifications. Determine the irrigated area, part 4, in acres by first estimating the wetted radius of the irrigated circle.

3. Determine the length of time required for the system to make a revolution by dividing the circumference of the outer wheel track by the speed of the end-drive unit. (See parts 10 and 11 in which the conversion constant is $60/(2 \times 3.14) = 9.44$.)

a. Stake out a known length along the outer wheel track and determine the time required for a point on the drive unit to travel between the stakes. The speed of travel will be the distance divided by the number of minutes. An alternate method is to determine the distance traveled in a given time.

b. Since many machines have uniform span lengths, excepting perhaps the first span, the radius between the pivot and the outer wheel track can normally be determined by multiplying the span length by the number of spans.

4. Estimate the width of the wetted pattern perpendicular to the lateral and the length of time water is received by the containers near the end drive unit (see part 12). The watering time is approximately equal to the pattern width divided by the speed of the end drive unit.

5. On water-driven systems, number each drive unit beginning with the one next to the pivot. Time how long it takes to fill a container of known volume with the discharge from the water motor in the outer drive unit and record in part 13. The exact method for doing this depends on the water motor construction and may require using a short length of hose.

6. If the system is equipped with a flow meter, measure and record the rate of flow into the system in part 14 of figure 11–55. Most standard flow meters indicate only the total volume of water that has passed. To determine the flow rate, read the meter at the beginning and end of a 10-min period and calculate the rate per minute. To convert from cubic feet per second (or acre-inches per hour) to gallons per minute, multiply by 450.

7. At the time the leading edge of the wetted patterns reaches the test area, set aside two containers with the anticipated catch to check evaporation losses. Measure and record in part 17 the depth of water in all the containers as soon as possible after the application has ended and observe whether they are still upright; note abnormally low or high catches. The highest accuracy can be achieved by using a graduated cylinder to obtain volumetric measurements. These can be converted to depths if the area of the container opening is known. For 1-quart oil cans, 200 ml corresponds to a depth of 1.0 in. Measure the catch of one of the evaporation check containers about midway during the catch reading period and the other one at the end.

Sample calculation 11-20.—Using center-pivot field test data.

Given:

The field data presented in figure 11-56.

Find:

Evaluate the system using the field data

Calculation:

The volumes caught in the containers must be weighted, since the catch points represent progressively larger areas as the distance from the pivot increases. To weight the catches according to their distance from the pivot, each catch value must be multiplied by a factor related to the distance from the pivot. This weighting operation is simplified by using the container layout procedure described earlier and figure 11-56 part 17.

The average weighted system catch is found by dividing the sum of the weighted catches by the sum of the catch position's numbers where containers were placed. Space for this computation is provided in parts 15 and 17.

For the average minimum weighted catch, an unknown number of containers that represents the low 1/4 of the irrigated area must be used. The low 1/4 is selected by picking progressively larger (unweighted) catches and keeping a running total of the associated position numbers until the subtotal approximates 1/4 of the sum of all the catch position numbers. The average weighted low 1/4 of the catch is then found by dividing the sum of the low 1/4 of the weighted catches by the sum of the associated catch position numbers. Space for this computation is also provided in parts 15 and 17.

To determine whether the system is operating at acceptable efficiency, evaluate the losses to deep percolation and DU by:

$$DU = \frac{\text{average weighted low quarter catch}}{\text{average weighted system catch}} \times 100 \qquad (11\text{-}3)$$

which for the example problem (fig. 11-56, part 15) is:

$$DU = \frac{0.42}{0.50} \times 100 = 84\%$$

This is a reasonable value and is independent of the speed of revolution.

It is useful to plot the volume of catch against distance from the pivot (fig. 11-57). Such a plot is useful for spotting problem areas, improperly located nozzles, and malfunctioning sprinklers. Usually there is excess water near each water-driven drive unit where the water is distributed as part of the pattern.

If the system is operating on an undulating or sloping field and is not equipped with pressure or flow regulators, DU will vary with the lateral position. The DU will remain nearly constant if the differences in elevation (in feet) multiplied by 0.43 (to convert to an equivalent psi) do not exceed 20 percent of the pressure at the end sprinkler. Thus, for the example test, the line position would have minimal effect on the DU since the pressure at the end sprinkler was 60 psi and the maximum elevation differences were only 25 ft, equivalent to 11 psi, which is only 18 percent of 60 psi.

The E_q can be determined if the pivot point is equipped with an accurate flow measuring device. To find the average low quarter application rate use the average weighted low one-quarter of the catches expressed as a depth per revolution. The average depth of water applied per revolution is calculated from equation 1 and from data computed on figure 11-56 in parts 11, 14, and 4. The depth applied per revolution is:

$$d = \frac{31.4 \times 1150}{453 \times 152} = 0.53 \text{ in}$$

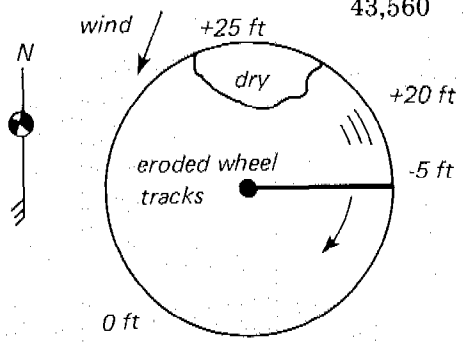
Since the R_e = (the average weighted catch)/d, equation 9 gives

$$E_q = DU \times \frac{\text{average weighted system catch}}{d}$$

$$= 84 \times \frac{0.50}{0.53} = 79\%$$

The small difference between DU of 84 percent and E_q of 79 percent indicates that evaporation losses are quite small and within the limits of measurement accuracy.

The system flow rate and E_q can be estimated without a flow meter at the inlet. This is done by first estimating the gross application by adding the average catch depth and the estimated evaporation, which for the data recorded in figure 11-56, parts 15 and 17, is 0.50 + .02 = 0.52 in

1. Location: *Field F202*, observer *JK*, date & time *8-12-71 p.m.*
2. Equipment: make *HG 100*, length *1375* ft, pipe diameter *6 5/8* in
3. Drive: type *water* speed setting *—%*, water distributed? *yes*
4. Irrigated area = $\frac{3.14 \text{ (wetted radius } 1450 \text{ ft)}^2}{43{,}560}$ = *152* acres
5. 

*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind *6* mph, temperature *90°F*

Pressure: at pivot *86* psi

at nozzle end *60* psi

Diameter of largest nozzle *1/2* in

Comments: *Sprinklers operating OK but end part circle sprinklers out of adjustment*

6. Crop: condition *corn, good except north edge*, root depth *4* ft
7. Soil: texture *sandy loam*, tilth *poor*, avail. moisture *1.0* in/ft
8. SMD: near pivot *0.5* in, at 3/4 point *0.5* in, at end *3.0* in
9. Surface runoff conditions at 3/4 point *slight*, and at end *moderate*
10. Speed of outer drive unit *45* ft per *10* min = *4.5* ft/min
11. Time per revolution = $\frac{\text{(outer drive unit radius } 1350 \text{ ft)}}{9.55 \text{ (speed } 4.5 \text{ ft/min)}}$ = *31.4* hr
12. Outer end: water pattern width *165* ft, watering time *39* min
13. Discharge from end drive motor *5.0* gal per *0.37* min = *13.5* gpm
14. System flow meter *11,500* gallons per *10* min = *1150* gpm
15. Average weighted catches:

System = $\frac{\text{(sum all weighted catches } 256{,}255)}{\text{(sum all used position numbers } 2044)}$ = *125* ml = *0.50* in

Low 1/4 = $\frac{\text{(sum low 1/4 weighted catches } 53{,}416)}{\text{(sum low 1/4 position numbers } 518)}$ = *104* ml = *0.42* in

16. Minimum daily (average daily weighted low 1/4) catch:

$\frac{\text{(24 hr operation/day)} \times \text{(low 1/4 catch } 0.42 \text{ in)}}{\text{(31.4 hr/revolution)}}$ = *0.32* in/day

17. Container catch data in units of *ml*, volume/depth *250* ml/in
Span length *90* ft, container spacing *22.5* ft

Evaporation:			
	initial	*150* ml	*150* ml
	final	*—147* ml	*—145* ml
	loss	*3* ml	*5* ml, ave *4* ml = *0.016* in

Figure 11–56.—Center-pivot sprinkle irrigation evaluation.

Span No.	Container			Span No.	Container		
	Position number	× Catch =	Weighted catch		Position Number	X Catch	Weighted Catch
1	1	Start numbering at		10	37	118	4366
1	2	pivot end of inner		10	38	127	4826
1	3	span. Do not wait		10	39	115	4485
1	4	for completion of		10	40	147	5880
2	5	irrigation at first		11	41	127	5207
2	6	few containers.		11	42	122	5124
2	7			11	43	118	5074
2	8			11	44	144	6336
3	9	141	1269	12	45	112	5040
3	10	160	1600	12	46	124	5704
3	11	122	1342	12	47	126	5922
3	12	130	1560	12	48	151	7248
4	13	143	1859	13	49	120	5880
4	14	150	2100	13	50	122	6100
4	15	134	2010	13	51	115	5865
4	16	123	1968	13	52	143	7436
5	17	144	2448	14	53	124	6572
5	18	138	2484	14	54	114	6156
5	19	135	2565	14	55	115	6325
5	20	107	4140	14	56	160	8960
6	21	122	2562	15	57	120	6840
6	22	114	2508	15	58	110	6380
6	23	115	2645	15	59	109	6431
6	24	138	3312	15	60	117	7020
7	25	109	2725	16	61	85	5185
7	26	113	2938	16	62	194	12028
7	27	114	3078	16	63	148	9324
7	28	126	3528	End	64	82	5248
8	29	116	3364		65	12	omit
8	30	107	3210		66		
8	31	122	3782		67		
8	32	140	4480		68		
9	33	117	3861		69		
9	34	105	3570		70		
9	35	111	3885		71		
9	36	125	4500		72		

Sum all: used position number 2044, weighted catches 256,255

Sum low 1/4: position numbers 514, weighted catches 53,416

Figure 11-56.—Center pivot sprinkle irrigation evaluation. (Cont.)

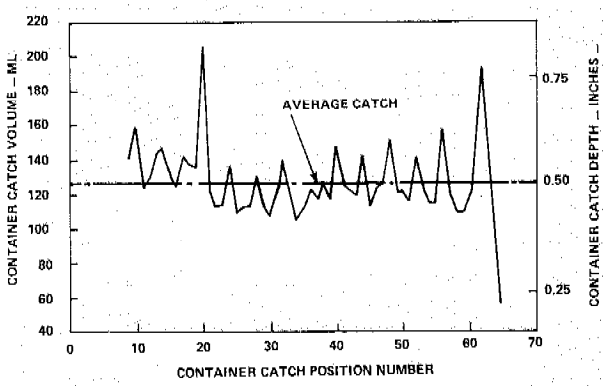


Figure 11-57.—Profile of container catch from center-pivot sprinkler evaluation test.

per revolution. The flow in gpm, which was distributed through the sprinkler, can be estimated by:

$$\text{Distributed flow} = \frac{453 \times \text{area (acres)} \times \text{gross application (in/rev)}}{\text{time per revolution (hr)}}$$

which for the recorded data is:

$$\text{Distributed flow} = \frac{450 \times 152 \times 0.52}{31.4}$$

$$= 1{,}133 \text{ gpm}$$

If water from the drive motor was not distributed, it must be added to the distributed flow to obtain the total system flow. The E_q is then computed as before by using the computed system flow. For the recorded data the drive water was included in the distributed flow and need not be computed. However, if it had not been included in the distributed flow, it should be estimated by:

$$\text{Drive flow} = \frac{\text{sum of drive unit numbers} \times \text{gpm flow from end water motor}}{\text{Number of drive units}}$$

For the 15 drive motors and a flow rate of 13.5 gpm from the end water drive motor:

$$\text{Drive flow} = \frac{120 \times 13.5}{15} = 108 \text{ gpm}$$

Runoff.—The computation of E_q is meaningful only if there is little or no runoff. Runoff or ponding may occur near the moving end of the system (fig. 11-58). Increasing the system's speed will reduce the depth per application and often prevent runoff; however, on some clay-type soils, decreasing the system's speed and allowing the surface to become drier between irrigations will improve the soil infiltration characteristics and reduce runoff even though the depth per application is increased. Therefore, both increasing and decreasing the speed should be considered. Other methods for reducing runoff include:

1. Using an implement called a pitter, which scrapes indentations in the furrows followed by small dikes every 2 or 3 ft.
2. Reducing the total depth of water applied per week by turning the system off for a period after each revolution. (Automatic stop devices are available for many systems.) This allows the surface soil to become drier between irrigations and thus have a higher infiltration capacity. Careful planning is required to avoid extensive underirrigation that may reduce crop yields.

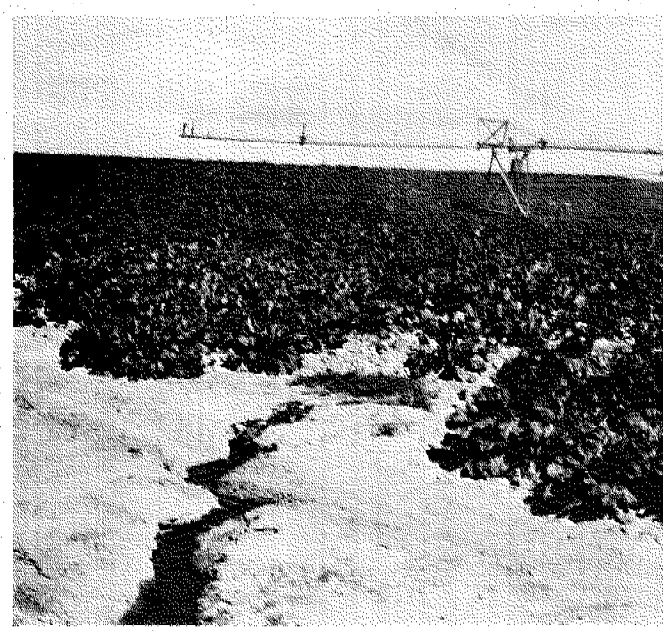


Figure 11-58.—Runoff near the moving end of a center-pivot lateral.

3. Decreasing sprinkler nozzle diameters to decrease the system capacity and application rate. All the nozzles must be changed to maintain uniformity.

4. Increasing system pressure and reducing nozzle sizes throughout the system to maintain the same system flow rate. This decreases the average drop size, lessens drop impact, and thereby reduces surface sealing that restricts infiltration.

5. Using special nozzles with pins to reduce drop sizes by breaking up the sprinkler jets.

6. Adherance to conservation practices that will limit runoff of water from fields. Contour farming, conservation tillage, terrace construction, and conservation cropping should all be considered.

Linear-Move System

Self-propelled linear-move laterals are among the latest innovations on the sprinkle irrigation market. The linear-move system must be fed by a hose pipe, or by water pumped from a channel that runs down the center or along the edge of the field.

The lateral pipe hydraulics are the same as for periodic-move system laterals because discharge and outlet spacing is uniform. Linear-move systems are usually operated at slow speeds and depths of application per irrigation are similar for both systems.

Because the laterals are continuously moving, the uniformity of application is very high under linear-move systems. Application rates are also usually high because it is attractive economically to irrigate as much area as possible with each lateral.

Sprinkler-Nozzle Configuration

The sprinkler-nozzle configuration used on linear-move laterals is similar to that used along the middle portions of center-pivot laterals. Therefore, many of the comments presented in the section on center pivots apply to sprinkler spacing, nozzle pressures, trajectory angles to surface sealing, application intensity and rate, and drift losses.

Application Rate.—Assuming that the application pattern under the sprinklers is elliptical, the average and maximum application rates under a linear-move lateral are:

$$I = \frac{93.3\ q}{S_\ell\ w} = \frac{96.3\ Q}{w\ L} \qquad \text{(11–52a)}$$

and

$$I_x = \frac{4}{\pi}\ \frac{96.3\ q}{S_\ell\ w} = \frac{122.6\ q}{S_\ell\ w} \qquad \text{(11–52b)}$$

where

I = the average application rate (iph)
q = the sprinkler discharge (gpm)
S_ℓ = the spacing between sprinklers in the lateral (ft)
w = wetted width of water pattern (ft)
Q = system discharge (gpm)
L = length of lateral (ft)
I_x = the maximum application rate (iph)

Application Depth.—The depth of water applied is a function of the application rate and lateral travel speed; however, lateral travel speed does not affect the application rate, which is controlled by sprinkler nozzle size and operating pressure. If the application decreases for any reason, the speed of lateral movement will likewise need to be reduced to apply the same total depth of water. This means a decrease in acreage that can be irrigated by the system in a given period.

The average gross depth of water applied per irrigation can be computed by equation 1.

The various types of sprinkle irrigation systems are adaptable to a variety of uses in addition to ordinary irrigation to control soil moisture. Automatic permanent, solid-set, and center-pivot systems are the most versatile multipurpose systems. Multipurpose systems make it possible to save labor, material, and energy by requiring fewer trips across the field with machinery and by permitting timely chemical applications. The most important multipurpose functions in addition to ordinary irrigation are applying fertilizers and soil amendments with the irrigation water, and applying herbicides and pesticides. The most important special use systems dispose of waste waters, prevent damage from frost, and provide control of the microclimate. Sprinkle equipment also provides farm fire protection, cooling and dust control for feedlots and poultry buildings, moisture for earth fill construction, and curing of log piles.

Federal, State, and Local Regulations

The use of chemicals is being strictly controlled by rapidly changing governmental regulations. Consult a reputable chemical dealer, county agricultural agent, state agricultural extension specialist, state department of agriculture, or the U.S. Environmental Protection Agency for those chemicals that are approved for application in irrigation water by sprinklers and on what crops the chemicals may be used.

Applying Fertilizers, Soil Amendments, and Pesticides

Dissolving soluble fertilizers in water and applying the solution through a sprinkler system is economical, easy, and effective. A minimum of equipment is required, and once the apparatus for adding the fertilizer to the irrigation water is set up, the crop being irrigated can be fertilized with less effort than is required for mechanical application.

Penetration of the fertilizer into the soil can be regulated by the time of application in relation to the total irrigation. An approximate ratio of 1 pound of fertilizer per gallon of water can be dissolved in water in a barrel or closed container, or liquid fertilizer can be used.

There are several advantages in using sprinkle irrigation systems as a means of distributing fertilizers. First, both irrigation and fertilization can be accomplished with only slightly more labor than is required for irrigation alone. This is particularly important in arid and semi-arid areas where the applications of irrigation water and fertilizers can, in most cases, be scheduled to coincide. Second, close control usually can be maintained over the depth of fertilizer placement as well as over the lateral distribution. The uniformity of fertilizer distribution can be only as good as the uniformity of water distribution, but if the sprinkle system has been properly designed and is properly operated, fertilizer distribution will be acceptable.

Injection Techniques.—The simplest way to apply fertilizer through a sprinkle system is to introduce the solution into the system at the suction side of a centrifugal pump (fig. 11-59). A pipe or hose is run from a point near the bottom of the fertilizer-solution container to the suction pipe of the pump. A shutoff valve is placed in this line for flow regulation. Another pipe or hose from the discharge side of the pump to the fertilizer container provides an easy method of filling the container, for dissolving the fertilizer, and for rinsing. If a closed pressure-type container is used, such as one of the several fertilizer applicators on the market, the line from the discharge side of the pump can be left open and the entrance of the solution into the water regulated by the valve on the suction side of the line.

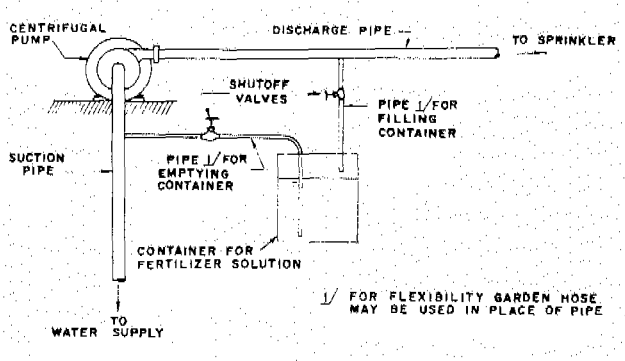


Figure 11-59.—A method for adding fertilizers in solution to a centrifugal pump system.

Fertilizer can also be added to sprinkler systems with a small high-pressure pump such as a gear or paddle pump (fig. 11-60). If a spray rig for orchards is available, the fertilizer solution can be pumped

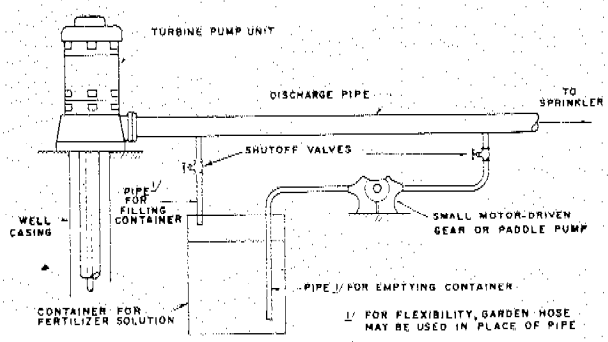


Figure 11-60.—A method for adding fertilizers to a turbine pump system using a small gear or paddle pump.

with the small pump on the spray rig. This method can also be used in applying fertilizer to individual sprinkler lines where more than one sprinkler line is operating at one time; however, it may be more cumbersome to move than other types of injectors. To avoid corrosion after the fertilizer solution is pumped into the line, the empty fertilizer barrel or container should be filled with water and water run through the pump. This operation should be repeated several times to rinse the pump and barrel thoroughly.

One common method of applying fertilizer through sprinkler systems is with an aspirator unit. Part of the water discharged from the pump is bypassed through the aspirator, creating suction that draws the fertilizer solution into the line. The objective is to create a pressure drop between the intake and outlet of the pressure-type container, thus creating a flow through the container into the sprinkler mainline or lateral. Several such commercial fertilizer applicators are on the market. One of these uses the pressure gradient through a Venturi section that has been inserted into the pipeline.

A second type operates on the pressure drop created by a pipe enlargement that creates sufficient pressure gradient without restricting flow. It is essential to have valves for regulating the flow through the aspirator and the main line. This type of fertilizer applicator costs about the same as a small gear or paddle pump unit and it has the advantage of simplicity and freedom from moving parts.

Fertilizer Materials

Many liquid, dry, and liquid suspension fertilizer materials are suitable for application through sprinkler systems. The main criteria used in selecting a fertilizer material are the convenience and cost of the desired nutrients.

Clear liquid fertilizers are very convenient to handle with pumps and gravity flow from bulk storage tanks. They may contain a single nutrient or combinations of nitrogen (N), phosphorus (P), and potassium (K). A wide variety of soluble dry fertilizers containing nitrogen, phosphorous and potassium singly or in combination are available for dissolution into the sprinkler irrigation stream. The dry fertilizer products may be dissolved by mixing with water in a separate, open tank and then pumped into an irrigation stream, or they may be placed in a pressurized container through which a portion of the sprinkler stream is passed. In the latter instance, the flow of water continuously dissolves the solid fertilizer until it has all been applied. Sprinkler application of dry fertilizer materials and agricultural minerals is increasing, because of improved application equipment and greater use of sprinklers.

Interest in suspension-type fertilizers has increased in recent years largely because of their potential for producing higher analysis and grades high in potassium. The suspension mixtures contain 11 to 133 percent more plant nutrients than correspondingly clear liquids. Because of their higher nutrient content, suspensions usually can be manufactured, handled, and applied at significantly less cost than clear liquids. Another advantage of suspensions is that they will hold relatively large quantities of micronutrients.

Only traces of many micronutrient materials can be dissolved in clear liquids. It is important that the irrigation water volume and velocity be sufficient to maintain the fertilizers in suspension or solution, in order to ensure proper dispersion and uniform distribution.

Materials commonly used for application through sprinkle systems are: urea-ammonium nitrate solutions, ammonium nitrate, ammonium sulfate, urea (potential NH_3 loss), calcium nitrate, potassium nitrate, liquid ammonium phosphates, some dry ammonium phosphates, potassium chloride (may be hard to dissolve), and potassium sulfate (may be hard to dissolve).

Secondary and micronutrients that can be applied through sprinkle systems include: magnesium sulfate, zinc sulfate and zinc chelates, manganese sulfate and manganese chelates, copper sulfate and copper chelates, iron sulfate and iron chelates, Solubor (boron), and molybdenum.

Materials that should *not* be applied through sprinkle systems include: aqua ammonia (excessive N loss and calcium precipitation with hard water); anhydrous ammonium (excessive N loss and will precipitate with hard water); single super phosphate, concentrated or treble superphosphate and some dry ammonium phosphates (materials that will not dissolve); potassium sulfate and magnesium sulfate (hard to dissolve); almost all N-P-K dry fertilizers, liming materials, and elemental sulphur (materials that will not dissolve); ammonium polyphosphate (precipitates with hard water), and phosphoric acid or any acid (causes corrosion and precipitation).

Fertilizer Applications

For periodic-move and fixed sprinkle systems, fertilizer should be applied by the batch method. With the batch method, the fertilizer required for a given area is put into a tank or metered into the system, and the solution is injected into the irrigation water. While high concentrations of solution must be avoided because of corrosion problems, exact proportions are not important. The sprinklers in operation at one time cover a specific area, and the quantity put into the tank (or metered into the system) at one time is the quantity that should go onto that area. Obviously, the entire batch should be used in a single set.

The common procedure followed in applying fertilizer by the batch method consists of three timed intervals. During the first interval, the system operates normally, wetting the foliage and the soil. During the second interval, the fertilizer in injected into the system. This application should rarely be less than 30 minutes and preferably an hour or longer. This eliminates the possibility of poor distribution due to slow or uneven rotation of sprinklers. Also, with normal fertilizer-application rates, the solution passing through the system will be better diluted. This lessens the possibility of foliage burn and corrosion damage to the system.

The last time interval should be long enough for the system to be completely rinsed with clear water and all fertilizer removed from plant foliage and moved down into the crop root zone. Depending on the rate of application at which the system is operating, the interval should continue for 30 minutes for fast rates, and 90 minutes for slower rates.

For continuously moving systems, such as center pivots, fertilizer must be applied by the proportional method. After applying fertilizer the system should be operated with clear water long enough to completely rinse it. With the proportional method the rate at which the fertilizer is injected is important since this determines the amount of fertilizer applied.

The application precautions are based on the fact that many commercial fertilizers and soil amendments are corrosive to metals and are apt to be toxic to plant leaves. With injection on the suction side of the pump, the approximate descending order of metal susceptibility to corrosion is as follows: (1) galvanized steel, (2) phosphobronze, (3) yellow brass, (4) aluminum, and (5) stainless steel. There are several grades of stainless steel, the best of which are relatively immune to corrosion. Protection is afforded by (a) diluting the fertilizer and (b) minimizing the period of contact with immediate, thorough rinsing after the application of chemicals. Avoid using materials containing heavy metals.

The steps in table 11–35 are for estimating the fertilizer application through a sprinkle system. Examples included are for applying urea-ammonium nitrate with 32 percent N and weighing 11.0 lb/gal through a 1/4-mile side-roll with 60 ft moves and through a 1/4 mile center pivot.

Applying Soil Amendments

Various soluble soil amendments, such as gypsum, sulphuric acid, lime, and soluble resins, can be applied through sprinkler systems. In the San Joaquin Valley of California, gypsum must be applied on many soils to reduce the percentage of soluble sodium that can cause poor infiltration by dispersing the soil particles. In this area, it is common practice to introduce gypsum through sprinkle irrigation systems. The methods used are generally the same as those used to add soluble fertilizers.

Applying Pesticides

Pesticides include herbicides, insecticides, fungicides, rodenticides, fumigants, and similar substances. The sale and use of these materials are regulated by state and federal laws. Many of the materials have been used effectively by growers and researchers; however, unless the chemicals have been cleared for use by the specific application method and under the specific conditions, do not use or experiment with them through sprinkle systems. Many people believe there is great potential for this method of pest control, especially through center-pivot and fixed systems, but more research is needed.

Table 11-35.—Steps for estimating fertilizer application through sprinkle systems

Step	Periodic move	Continuous move
1. Decide on amount of nitrogen to apply	40 lb/ac	30 lb/ac
2. Select kind of nitrogen fertilizer and % N	32%	32%
3. Determine gallons (or pounds) per acre[1]	11.4 gal/ac	8.5 gal/ac
4. Determine number of acres irrigated per set or turns[2]	1.82 ac	125.7 ac
5. Determine the gallons (or pounds) required per set or turn	20.7 gal	1,068 gal.
6. Determine the length of the application time[3]	1 hr	24 hr
7. Calculate the required fertilizer solution injection rate[4]	21 gph	44.5 gph

[1] Dry fertilizers must be dissolved and put in a liquid form in order to be injected continuously into the system (40/0.32)/11 = 11.4 gal/ac.

[2] For periodic-move, fixed, traveling sprinkler, and linear-move systems use the area covered per set. For center-pivot systems use the area covered in a complete revolution.

[3] For periodic-move and fixed systems use some convenient portion of the set time. For continuous-move systems use the length of time required to complete a run or revolution.

[4] For periodic-move systems the injection rate only needs to be approximate. For continuous-move systems it must be accurately controlled for precise applications of fertilizers. If the injection pump has fixed injection rates the travel speed of continuous-move systems can be adjusted for precise applications.

Diluted solutions of the basic fertilizers and herbicides can be applied throughout the irrigated area during the ordinary irrigation operations. The program for foliar applications of trace elements and most pesticides is similar to the foliar cooling operation with fixed systems. The chemicals are added in precise quantities to the irrigation water to form diluted solutions. The system is then cycled so that the application time is just enough to wet thoroughly the foliage and the "off" time is sufficient for each application to dry. This process, which coats the leaves with thin layers of the chemical, is repeated until the desired amount of chemical is applied.

Disposing of Wastewater

Land application of wastewaters by sprinkle irrigation can be a cost-effective alternative to conventional wastewater treatment. Wastewaters are divided into municipal, industrial, and agricultural categories. Wastewaters from most cities require rather extensive treatment before discharge. Industrial wastewaters can require extensive pretreatment, ranging from simple screening to primary and secondary treatment for removing oils, greases, metals, and harmful chemicals; for pH adjustment and for chlorination. Agricultural wastewaters include effluents from animal production systems and food processing plants. For land application through sprinkle irrigation, most animal wastes must undergo some treatment, such as removal of large fibrous solids. Wastewaters from food processing plants generally require more extensive pretreatment such as removal of solids, greases, and oils and adjustments in pH.

Design Considerations

Major concerns for land application of wastewaters with sprinkle systems are that the wastewater be of good quality and be applied in such a fashion that it will not destroy or render ineffective the disposal site or pollute ground and surface water in neighboring areas. Oils, greases, and heavy metals can harm the soil and the vegetative cover. Furthermore, excessive solids can build up a mat on the surface that will destroy the vegetative cover.

In designing a sprinkle irrigation system, the effluent, vegetative cover, soil type, and frequency of application should be considered. Well-drained, deep sandy or loamy soils are often suitable for land application of wastes. Some soils may require subsurface drainage. The application rate should not exceed the infiltration rate of the soil, and most recommendations are for a maximum application rate of 0.25 iph. The total application per week can vary between 1 and 4 in, with the higher application during the summer months. There should be a rest period between applications, however.

Woodland can be a good disposal site for wastewaters. In woodlands, the soil surface is stable and the surface cover is effective for digesting organic matter. If grassland is used, it is important to se-

lect a grass that is specific for the site. Corn can also be grown on a disposal site, but effluent can be applied only at selected times of the year. Rates of nitrogen that can be applied will range from approximately 200 lb/ac per year for corn to 700 lb/ac per year for coastal Bermudagrass. Nitrogen application in excess of plant use can result in leaching of nitrate and pollution of the ground water.

Hardware

Most land disposal sprinkle systems use single-nozzle sprinklers. This reduces nozzle clogging problems and also results in a lower application rate. If systems are designed to operate during freezing temperatures, sprinklers that will operate under these conditions should be selected. Either portable aluminum or buried pipe may be used for main and lateral lines of periodic-move or fixed systems; however, noncorrosive buried pipe is recommended. For fixed systems designed to operate continuously, automation is recommended. Automatic valves can be operated by air, water, or electricity. However, the most desirable are either air or water valves with water from a clean source. Solids in the wastewater tend to clog the electric solenoid valves.

Valves for fixed systems should be located in a valve box, numbered, and color coded. If the site is in a freezing climate, drain valves should be installed to drain the pipe system. The most positive freeze protection system is an air purge system that can be used to clear the pipe of water. Where the system is operated only part of the time, and the wastewater is corrosive or has a high solids content, the system should be flushed with fresh water after each use. Effluents left in the pipes will become septic and create a nuisance. Also, suspended solids will settle and harden at low points in the lines and may cause severe clogging.

Center-pivot and traveling sprinklers are used in addition to portable aluminum pipe and fixed irrigation systems for land application of wastewaters. Both of these systems have fairly high application rates. Effluents with high levels of suspended solids may clog the turbine or piston on water-drive traveling-gun sprinklers. Furthermore, the operation of large impact sprinklers during windy weather can create severe drifting problems. For this reason, many center-pivot effluent disposal systems are now equipped with spray nozzles directed downward. Traction problems can also occur in center-pivot systems, because of the large amounts of water applied.

The design of a sprinkle irrigation system for land application of wastewater is similar to the design of other types of sprinkle irrigation systems. The designer must follow the rules of good design, keeping in mind that the effluent is not water, but a mixture of water and solids, and that wastewaters that are abrasive or corrosive will shorten the life of the system. Therefore, special equipment may be required.

Frost Protection

Sprinkle irrigation can be used for frost protection as discussed in *Capacity Requirements* for fixed systems. However, an ordinary system is limited because of the area it can cover at any one setting of the lateral lines. Therefore, for adequate protection of most areas, it is necessary to add capacity so that the entire field can be watered. The application rate and system capacity requirements for different levels of protection were presented earlier. Since an application rate of about 0.1 iph is usually sufficient, small single-nozzle sprinklers are satisfactory; however, double-nozzle sprinklers can be used by plugging one nozzle. Nozzle sizes from 3/32 to 1/4 in have been successfully used for overhead frost protection, with the size depending on the spacing.

Short-duration, light-radiant frosts (down to 28° or 29° F) can be protected against with under-tree misting or by cycling an overhead system with 2- to 4-min applications every 4 to 8 mins so that half the system is always operating. Such systems require about 25 to 30 gpm per acre, half as much water as is needed through continuously operating full coverage systems.

Usually wind speeds are very low during periods when frost protection is possible. Therefore, wetted diameters taken from manufacturers' catalogues or from table 11-13 can be used with the standard reduction for developing sprinkler spacing criteria. Typical single-nozzle sprinklers recommended for frost protection systems produce D profiles and can be spaced at 75 percent of the wetted diameter and still give adequate coverage as shown in figure 11-22. Sprinkler pressures should be maintained on the high side of the recommended operating range, and rotation speeds of impact sprinklers should be 1 rpm or faster for best results.

Frost Control Operation

For complete frost control, a continuous supply of water must be available. The water supply capacity must exceed the atmospheric potential to freeze the water; in other words, some water should always be left on the plants. The mechanics of frost control depend upon the fact that water freezes at a higher temperature than do the fluids in the plant. Therefore, as long as there is water available to be frozen, the temperature will be held at 32°F, higher than the freezing point of the plant fluids.

The temperature of a wet surface will equal the wet bulb or dew point temperature, which is lower than the air temperature. Therefore, frost control systems should be turned on when the air temperature approaches 33°F. The field becomes a mass of ice and yet the ice remains at a temperature above the freezing point of the plant liquid as long as water is being applied. Damage also can occur if the water is turned off too soon after the temperature climbs above 32°. Therefore, for adequate protection, one should continue to apply water until the air temperature is above 32°F, and all the ice has melted off the plants.

Some type of electric alarm system should be installed so that the farmer will know when to get up at night to turn on the system. A thermo-switch set in the field at plant level with wires to the house and with a loud bell alarm will serve this purpose. The switch should be set so that the bell sounds when the plant-level temperature reaches 34°. The system should be laid out and tested well in advance of the time that it may have to be used.

Frost protection with sprinklers has been used successfully on trees, bushes, vines and low-growing vegetable crops such as tomatoes, cucumbers, peppers, beans, cranberries, and strawberries. During low-temperature frosts the ice that accumulates on trees can be heavy enough to break the branches. Similar ice accumulation could break down sweet corn, celery, pole beans, and tall flowers. For this reason, tall, thin plants are not generally adapted to frost protection by ice encasement.

Bloom Delay

In the fall, deciduous trees, vines and bushes lose their leaves and enter a condition known as dormancy. Plants are normally incapable of growth during this period, and fruit buds do not develop until they break dormancy sometime between midwinter and early spring. The rate of bud development depends on the air temperature around the buds. If the early spring temperatures are cool, blossoming is delayed; however, when spring temperatures are above normal, bud development accelerates and the trees blossom early. If early bud development is followed by a sudden cold spell, the potential for freeze damage becomes serious. For example, Utah fruit growers suffered losses due to freeze damage nine of the years between 1959 and 1973 as a result of freezes occurring after warm early spring temperatures caused the buds to develop to a sensitive stage.

In the past, the common practice has been to use sprinklers to supply heat to the orchard for protection from freezing that occurs after the buds have developed to a sensitive stage. A new procedure is to cool the trees by sprinkling before the buds develop and thus to keep them dormant until after the major danger of freeze damage is past.

After dormancy, any time the temperature rises above 40°F the buds will show signs of development. The rate of development increases as the temperature increases until the ambient air temperature reaches 77°F. Thereafter the rate of development does not change appreciably with increasing temperature. The energy accumulation associated with bud development is called "growing degree hours." As the buds continue to develop in the spring their susceptibility to damage from low temperatures increases.

Tests have shown that each fruit species has different chill unit requirements to complete dormancy and different growing degree hour accumulations to reach the various stages of phenological development. The system capacity required for bloom delay is discussed in *Capacity Requirements for Fixed Systems.*

The amount of evaporative cooling that takes place on bare limbs depends on: (a) the temperature of the tree buds, (b) the difference in vapor pressure between the bud surface and the air, and (c) the rate at which evaporated water is removed from the boundary layer by diffusion or by wind currents. Therefore, for maximum cooling with the least amount of water application, it is necessary to completely wet the buds periodically and to allow most of the water to evaporate before rewetting.

The design and operation of bloom delay systems are still in the development stage. However, the current state of the art indicates the following for the Great Basin area:

1. Overtree sprinkling to provide evaporative cooling will delay budding of deciduous fruit trees. Tests indicate that over 80 percent of the damage from early spring freezes can be prevented.

2. Starting the sprinkler on the day when the mathematical model predicts winter rest is completed minimizes guesswork, provides maximum protection, and saves water.

3. Shrub-type sprinkler heads can be programmed to cycle on and off as a means of saving water; however, the installation costs are greater than for impact-type sprinklers.

4. In the early spring, less water is required to provide adequate cooling and protection. Water can be saved if (a) the off portion of the watering cycle is long in the early spring and is decreased as daytime temperatures rise, (b) a smaller nozzle is used in impact sprinklers in the early spring, and (c) pump output is low in the early spring and is increased as daytime temperatures rise.

5. Impact sprinklers, with 9/64-in nozzles on spacings of 40 x 50 ft operating at 40 psi and cycled on and off each 2 min have given good protection under most conditions.

6. Sprinkling for bloom delay can be combined with ice encasement sprinkling for freeze protection. The former can be used in the early spring and the latter in late spring.

Microclimate Control

Crop or soil cooling can be provided by sprinkle irrigation. Soil cooling can usually be accomplished by applications once or twice every 1 or 2 days. Therefore, ordinary fixed systems with or without automatic controls and center-pivot systems with high speed drives are suitable for soil cooling.

Foliar cooling requires two to four short applications every hour; therefore, only automated fixed systems can be used. The small amounts of water intermittently applied cool the air and plant, raise the humidity, and in theory improve the produce quality and yield. By supplying water on the plant surfaces, the plant is cooled and the transpiration rate reduced so that a plant that would wilt on a hot afternoon can continue to function normally. The management and value of cooling systems, however, need further study.

On low crops and vines, a 3-min application at 0.1 iph every 15 min has usually been adequate to reduce temperature 10° to 20°F when the humidity is 20 to 40 percent and the air temperature is over 95°F. On larger trees, a 6-min application every 30 to 36 min has been satisfactory. Foliar cooling is possible only with *very high* quality water. The capacity requirements and system design procedures of fixed systems that are designed for foliar cooling are discussed in *Capacity Requirements for Fixed Systems.*

System design procedures follow the general guidelines presented in *Design Procedures.*

Installation and Operation of Sprinkle Systems

The best prepared plan contributes little or nothing toward obtaining the objective of conservation irrigation and maximum yields of high-quality crops unless the farmer purchases substantially the equipment specified in the plan, installs the equipment properly, and operates it according to design.

The installation of sprinkle irrigation systems may be the responsibility of the engineer, the dealer, the farmer, or any combination of the three depending on the financial and physical arrangements made by the farmer.

A plan of the system should be furnished to the farmer that includes a map of the design area or areas showing the location of the water supply and pumping plant; the location of supply lines, main lines, and submains; the location and direction of movement of lateral lines; the spacing of sprinklers; and the pipe sizes and length of each size required. While it is not necessary to furnish the farmer with a complete list of materials, minimum equipment specifications should be furnished. These include the discharge, operating pressure, and wetted diameter of the sprinklers, the capacity of the pump at the design dynamic head; and the horsepower requirements of the power unit. Fittings for continuous operation should be specified where applicable.

Farmers may receive sprinkle-system plans prepared by SCS engineers, and then purchase equipment that is entirely different from that specified in the plans. While SCS personnel do not have any responsibility for or control over the purchase of sprinkler equipment by the farmer, it is important, nevertheless, to emphasize to the farmer the necessity of purchasing a satisfactory system. A sprinkle system should give suitable uniformity, have the capacity to supply crop water requirements throughout the season, and be designed to conserve energy.

The farmer should be given instruction in the layout of main lines and laterals, the spacing of sprinklers, the movement of lateral lines, the time of lateral operation, and the maintenance of design operating pressures. He also should be shown how to estimate soil-moisture conditions in order to determine when irrigation is needed and how much water should be applied.

Ideally, irrigation scheduling should be managed so that optimum production is achieved with a minimum of expense and water use. Nearly perfect irrigation should be possible with fixed and center-pivot systems. The soil moisture, stage of crop growth, and climatic demand should be considered in determining the depth of irrigation and interval between each irrigation. For each crop-soil-climate situation, there is an ideal irrigation management scheme.

Irrigation scheduling should be guided either by devices that indicate the soil-plant water status or by estimations of climatic evaporative demand. Computerized scheduling services based on climatic demand prove to be an ideal tool for managing sprinkle systems.

Appendix

Sprinkle Abbreviations

A	design area (acres)
B	nozzle size (1/64 in)
BHP	brake horsepower (hp)
C	friction coefficient of pipe
CE	present annual energy cost of system operation ($)
CE′	annual energy cost of overcoming head loss ($)
CI	coarseness index (%)
CRF	capital recovery factor
CU	coefficient of uniformity (%)
CU_a	coefficient of uniformity for alternate sets (%)
D	inside diameter of pipe (in)
d	gross depth of application (in)
d′	daily gross depth of application required during peak moisture use period (in)
DU	distribution uniformity (%)
DU_a	distribution uniformity for alternate sets (%)
E	elevation difference (ft)
E_h	application efficiency of lower half (%)
E_p	pump efficiency (%)
E_q	application efficiency of the low quarter (%)
e	equivalent annual rate of energy escalation (decimal)
EAE(e)	equivalent annualized cost factor of escalating energy
ET	crop water consumption (in/day)
F	multiple outlet reduction coefficient
f	time allowed for completion of one irrigation (days)
H_e	total head change due to elevation (ft)
H_f	total head loss due to pipe friction (ft)
H_{fl}	limit of friction loss in length of pipe (ft)
h_e	head change due to elevation (ft)
h_f	head loss due to pipe friction (ft)
I	average application rate (iph)
I′	preliminary application rate (iph)
I_i	instantaneous application rate (iph)
I_t	approximate actual application rate from a traveling sprinkler (iph)
i	annual interest rate (decimal)
J	head loss gradient (ft/100 ft)
J_a	allowable headloss gradient (ft/100 ft)
K	resistance coefficient of fitting or valve
K_{cp}	discharge coefficient of a center pivot
K_d	combined sprinkler and nozzle discharge coefficient
K_f	Skobey friction coefficient
K_s	coefficient or function of I, S_l and k_d
L	length of pipe (ft)
L′	length of pivot to last drive unit (ft)
M	irrigation system cost ($)
MAD	management allowable depletion (%)
N	number of outlets (may be laterals off mainline or sprinklers operating off laterals)
N_n	minimum usual number of sprinklers operating
N_x	maximum usual number of sprinklers operating
n	number of years in life cycle
P	nozzle operating pressure (psi)
P_a	average sprinkler pressure (psi)
P_{cp}	inlet pressure measured at the top of the pivot point (psi)
P_{cv}	pressure loss at the control valve (psi)
P_e	pressure change due to elevation (psi)
P_f	pressure loss due to pipe friction (psi)
P_m	pressure required at lateral inlet (psi)
P_n	minimum sprinkler pressure (psi)
P_r	pressure required to lift water up risers (psi)
P_x	maximum sprinkler pressure (psi)
PW(e)	present worth of escalating energy costs ($)
Q	system discharge capacity (gpm)
Q_r	pivot lateral flowrate at r (gpm)
Q_s	total system capacity (gpm)
q	sprinkler discharge (gpm)
q_a	average sprinkler discharge (gpm)
q_g	end gun discharge (gpm)
q_r	sprinkler discharge at r (gpm)
R	maximum radius irrigated when corner system or end sprinkler is in operation (ft)
R_e	effective portion of applied water (%)
R_w	radius of pivot to the location of the weighted average elevation (ft)
r	radius from pivot to point under study (ft)
S_a	angular segment wetted by sprinkler jet (degrees)
S_l	spacing of sprinklers along laterals (ft)
S_m	spacing of laterals along mainline (ft)
S_r	sprinkler spacing on pivot lateral (ft)

T	actual operating time (hr/day)
t	wetted radius (ft)
TDH	total dynamic head (ft)
U	present annual power cost ($)
U′	equivalent annual energy cost ($)
V	velocity of flow (ft/s)
v	travel speed of end drive unit (ft/s)
W	towpath spacing (ft)
w	wetted width of water pattern (ft)
WHP	water horsepower (hp)
ω	portion of circle receiving water (degrees)
X	length of smaller pipe (ft/100 ft)
Y	length of pipe of specified diameter

Sprinkle Equations

11-1 $$Q = \frac{453\ Ad}{fT}$$

11-2 $$I = \frac{96.3 \times q}{S_t \times S_m}$$

11-2a $$I_i = \frac{96.3 \times q}{\pi (R_j)^2 \times S_a/360°}$$

11-3 $$DU = \frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} \times 100$$

11-4 $$CU = 100\left(1.0 - \frac{\Sigma X}{mn}\right)$$

11-4a $$CU \cong \frac{\text{Average low-half depth of water received}}{m} \times 100$$

11-5a $$CU = 100 - 0.63\,(100 - DU)$$

11-5b $$DU = 100 - 1.59\,(100 - CU)$$

11-6a $$CU_a = 10\sqrt{CU}$$

11-6b $$DU_a = 10\sqrt{DU}$$

11-7 $$CI = \frac{P^{1.3}}{B}$$

11-8 $$R_e = \frac{(CI-7)}{10}(R_e)_c + \frac{(17-CI)}{10}(R_e)_f$$

11-9 $$E_q = DU \times R_e$$

11-10 $$E_h = CU \times R_e$$

11-11a $$\text{System } DU = DU \times \left(1 - \frac{P_x - P_n}{5\,P_a}\right)$$

11-11b $$\text{System } CU = CU \times \left(1 - \frac{P_x - P_n}{8\,P_a}\right)$$

11-12 $$q = K_d\sqrt{P}$$

11-13a $$q = q'\sqrt{P/P'}$$

11-13b $$P = P'(q/q')^2$$

11-14a $$N_n = \frac{Q}{q_a}$$

11-14b $$Q = N_x \times q_a$$

11-15 $$J = \frac{h_f\,100}{L} = 1050\left(\frac{Q}{C}\right)^{1.852} D^{-4.87}$$

11-16a $$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2}$$

11-16b $$F = \left(\frac{2N}{2N-1}\right)\left(\frac{1}{m+1} + \frac{\sqrt{m-1}}{6N^2}\right)$$

11-17a $$h_f = JFL/100$$

11-17b $$P_f = \frac{JFL}{231} = h_f/2.31$$

11-18a $$J_a = \frac{0.20\,P_a \times 2.31}{L/100 \times F}$$

11-18b $$J_a = \frac{(0.20\,P_a - P_e) \times 2.31}{L/100 \times F}$$

11-18c $$J_a = \frac{(0.20\,P_a + P_e) \times 2.31}{L/100 \times F}$$

11-19a $$P_m = P_a + 3/4\,P_f + P_r$$

11-19b $$P_m = P_a + 3/4\,P_f + 1/2\,P_e + P_r$$

11-19c $$P_m = P_a + 3/4\,P_f - 1/2\,P_e + P_r$$

11-20a $P_m = P_a + 2/3\ P_f + P_r$

11-20b $P_m = P_a + 2/3\ P_f + 1/2\ P_e + P_r$

11-20c $P_m = P_a + 2/3\ P_f - 1/2\ P_e + P_r$

11-21 $P_f = P_{f(1+2)}$ (for D_1) $- P_{f(2)}$ (for D_1) $+ P_{f(2)}$ (for D_2)

11-22a $P_m = P_a + P_f + P_r + P_{cv}$

11-22b $P_m = P_a + P_f + P_e + P_r + P_{cv}$

11-22c $P_m = P_a + P_f - P_e + P_r + P_{cv}$

11-23a $J = \dfrac{h_f}{L/100} = 0.133\ \dfrac{Q^{1.75}}{D^{4.75}}$ (for $D < 5$ in)

11-23b $J = \dfrac{h_f\ 100}{L} = 0.100\ \dfrac{Q^{1.83}}{D^{4.83}}$ (for $D > 5$ in)

11-24 $J = \dfrac{h_f\ 100}{L} = \dfrac{K_f}{10}\ \dfrac{V^{1.9}}{(D/12)^{1.1}}$

11-24a $H_{f1} = X\ J_2 + (L_1 - X)\ J_1$

11-24b $X = \dfrac{H_{f1} - J_1 L_1}{J_2 - J_1}$

11-25a $H_{f2} = J_1\ L_{d1} + J_2 L_{d2} + J_3\ (L_2 - Y) + J_4 Y$

11-25b $Y = \dfrac{H_{f2} + J_1 L_{d1} - J_2 L_{d2} - J_3 L_{d2}}{J_4 - J_3}$

11-26 $PW(e) = \left[\dfrac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\dfrac{1}{(1+i)^n}\right]$

11-27 $EAE(e) = \left[\dfrac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\dfrac{i}{(1+i)^n - 1}\right]$

11-28 $CRF = \dfrac{i(1+i)^n}{(1+i)^n - 1}$

11-29 $U = \dfrac{1{,}000\ \text{hr/yr} \times \$0.07/\text{BHP-hr}}{0.75\ \text{WHP/BHP}}$

11-30 $WHP(6-8) = \dfrac{\$10.70/100\ \text{ft-yr}}{\$138.60/\text{WHP-yr}}$

$= 0.077\ \text{WHP}/100\ \text{ft}$

11-31 $V = 0.4085\ \dfrac{Q}{D^2}$

11-32 $CE' = \dfrac{EAE\ U\ Q_s}{3{,}960}\ H_f$

11-33 $h_f = K\ \dfrac{V^2}{2g}$

11-34 $\dfrac{V^2}{2g} = 0.002592\ \dfrac{Q^2}{D^4} = \dfrac{Q^2}{386\ D^4}$

11-35a $S_m = \dfrac{96.3\ K_d\ \sqrt{P}}{I - S_l}$

11-35b $S_m = K_s\ \sqrt{P}$

11-36 $BHP = \dfrac{Q_s \times TDH}{3{,}960\ E_p/100}$

11-37 $CE = \dfrac{U\ Q_s\ TDH}{3{,}960}$

11-38a $R_e = \dfrac{\text{average catch rate (or depth)}}{\text{application rate (or depth)}}$

11-38b $R_e = \dfrac{\text{average catch rate}}{96.3\ q/(S_l \times S_m)}$

11-39 $I_t = \dfrac{96.3\ q}{\pi(0.9t)^2} \times \dfrac{360}{\omega}$

11-40 $d = \dfrac{1.605\ q}{W\ S}$

11-41a acres covered per hour $= \dfrac{W\ S}{726}$

11-41b acres irrigated per 1/4-mile run $= \dfrac{W}{33}$

11-42a $Q = 18.9\ A\ d'$

11-42b $Q = \frac{R^2 d'}{734}$

11-42c $Q = \frac{453A\ d'}{T}$

11-43a $I = \frac{2(96.3)\ r\ Q}{R^2\ w}$

11-43b $I_x = \frac{4}{\pi}\ \frac{2(96.3) r\ Q}{R^2\ w}$

11-44 $q_r = r\ S_r\ \frac{2\ Q}{R^2}$

11-45 $Q_r = Q\ (1 - \frac{r^2}{R^2})$

11-46 $q_g = Q(1 - \frac{L^2}{R^2})$

11-47 $(H_f)_{cp} = 5.7\ L\ (\frac{Q}{C})^{1.852} D^{-4.87}$

11-48a $(H_f)_{cp} = (H_f)_R - (H_f)_{R-L}$

11-48b $(H_f)_{cpg} = 5.7\ R'\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$

11-49 $v = \frac{2\ \pi\ L'}{60\ fT}$

11-50 $Q_2 = K_{cp}\ \sqrt{P_{cp2}} = Q_1\ (\frac{P_{cp_2}}{P_{cp_1}})^{1/2}$

11-51a $R_w = \frac{L}{3Q}\ (2Q + q_g)$

11-51b $R_w = \frac{2L}{3} + \frac{L}{3}\ (1 - \frac{L^2}{R^2})$

11-52a $I = \frac{96.3q}{S_t\ w} = \frac{96.3\ Q}{wL}$

11-52b $I_x = \frac{4}{\pi}\ \frac{96.3\ q}{S_t\ w} = \frac{122.6\ q}{S_t\ w}$

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Section 15

IRRIGATION

Chapter 12

LAND LEVELING

Soil Conservation Service
United States Department of Agriculture

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 12--LAND LEVELING

CONTENTS

	Page
General	12-1
Description	12-1
Criteria for land leveling	12-1
Preparatory steps	12-2
Surveys	12-4
Planning surveys	12-4
Design and construction surveys	12-4
Land Leveling Design Methods	12-7
General	12-7
The plane method	12-7
Subdivide the field into subareas	12-7
Locate the centroid	12-9
Determine the average elevation of the field	12-11
Compute the slope of the plane of best fit	12-11
Determine the elevation of the plane at the centroid	12-15
Compute the elevation for each grid point	12-16
Compute the cuts and fills	12-16
The profile method	12-18
Plot the profiles	12-18
Establish trial gradelines	12-20
Examine the grades between profiles	12-20
Compute the cuts and fills	12-23
The plan-inspection method	12-23
The contour-adjustment method	12-26
Earthwork Calculations	12-29
Earthwork volumes	12-29
The four-point method	12-29
The end-area method	12-32
The horizontal-plane method	12-34
The summation method	12-35
Comparison of methods	12-35
Earthwork balance	12-36

CONTENTS--Cont'd

	Page
Construction	12-37
General	12-37
Equipment	12-37
Construction procedure	12-38
Preservation of topsoil	12-40
Construction tolerance	12-41
Checking	12-41
Finishing	12-42
Maintenance	12-42
Special practices	12-42
Contour-bench leveling	12-42
Bench cross sections	12-43
Bench location	12-45
Location of guidelines	12-46
Planning benches	12-51
Staking	12-53
Computing cuts and fills	12-56

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 12--LAND LEVELING

FIGURES

Figure		Page
12-1	Grid map for land leveling	12-6
12-2	Field subdivision for leveling	12-8
12-3	Location of the centroid of a field	12-10
12-4	Determination of plane of best fit	12-12
12-5	The plane method of land leveling	12-17
12-6	The profile method of land leveling	12-19
12-7	The profile method of land leveling	12-21
12-8	Two-way method of plotting profiles	12-22
12-9	The plan-inspection method of land leveling	12-25
12-10	The contour-adjustment method of land leveling	12-27
12-11	Construction map for land leveling	12-39
12-12	Contour-bench relationships	12-44
12-13	Establishing guidelines for contour-bench leveling from contour map	12-47
12-14	Establishing guidelines for contour-bench leveling from grid map	12-50
12-15	Contour-bench leveling layout	12-52
12-16	Contour-bench details	12-54
12-17	Staking contour benches - method 1	12-55
12-18	Staking contour benches - method 2	12-57
12-19	Leveling calculations for contour benches	12-58

TABLES

Table		Page
12-1	Relief classes for surface irrigated land	12-3
12-2	Constants for determination of plane of best fit	12-14
12-3	Earthwork quantities in cubic yards with 100-foot land-leveling grid	follows 12-30

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 12--LAND LEVELING

General

Description.
Land leveling or land grading for irrigation is modifying the surface relief of a field to a planned grade to provide a more suitable surface for efficiently applying irrigation water.

Normally land leveling requires moving a lot of earth over several hundred feet. This should not be confused with land planing, land smoothing, or land floating. They are usually accomplished with special equipment to eliminate minor irregularities, and they do not change the general topography of the land surface.

Rough grading is removing knolls, mounds, or ridges and filling pockets or swales in a field that is not to have a planned grade. Often no construction stakes are set and reliance is placed on the "eye" of the equipment operator to obtain the desired field surface. Rough grading is seldom adequate for lands to be surface irrigated.

Criteria for Land Leveling.
Criteria for land leveling will be influenced by the soil, slope, climate, crops to be grown, methods of irrigation, and the desires of the farmer.

Land leveling should never be planned without knowing the soil-profile conditions and the maximum cut that can be made without seriously affecting agricultural production. Shallow soils that require strict limitations on permissible depth of excavation do not permit much freedom to the designer. They pose a difficult problem when combined with undulating topography or steep slopes.

The climate of an area often places certain limits on slope to prevent erosion from rainfall or to provide adequate drainage. Also crops to be grown need to be known since they will affect the irrigation methods selected and will provide an idea as to the amount of leveling needed. Intensively cultivated crops such as vegetables may justify a high leveling cost whereas a hay crop in an area with a short growing season may warrant a much smaller investment.

Each method of irrigation has limitations. When several methods of irrigation are to be used on the same field, the requirements of the most restrictive must be met. The level border method is the most restrictive of all irrigation methods. In general, flooding methods have the strictest cross-slope requirements.

The desires of the farmer must also be known in selecting the design standards for a specific job. Minimum conservation-irrigation standards must be met. Oftentimes the farmer desires to have a still better job that will save on labor and permit better farming practices. The engineer should attempt to design the best job the farmer is willing to accept and pay for. Usually the standards of the farmers go up from year to year, and a job that is perfectly satisfactory today may be considered substandard tomorrow. Many fields have been leveled and re-leveled several times, each time to a higher standard. Obviously the number of times a field is leveled should be held to a minimum. Therefore, it is desirable to design as refined a job as the soil and farmer will permit.

It is generally accepted that the most desirable field surface for agricultural production is a plane surface on a nearly level grade. Likewise, the least desirable is one with such surface relief that irrigation can barely be accomplished and that unusually good management is required to obtain even fair irrigation water efficiencies.

Table 12-1 is a classification of surface relief as it affects irrigation. In some areas Class A_1 might be the only one to consider, whereas in others with shallow soils and steep slopes, Class E may be the best physically obtainable. The least restrictive class permissible may be established at a State level based on climate and other conditions.

Class C is the lowest usually considered satisfactory for conservation irrigation by surface methods. When it is impossible, however, to bring the surface to this standard, special justification should be present before surface methods are recommended. Usually sprinkler methods are best for these sites.

Preparatory Steps.

Land leveling is usually accomplished on a field by field basis. It is extremely important, therefore, to study the entire farm before attempting any leveling.

Land leveling is probably the most intensive practice that is applied to agricultural lands, and much expense can be saved by carefully dividing the farm into areas that have about the same slope and soil characteristics. These areas will provide a basis for selecting the proper field arrangement.

Table 12-1.--Relief classes for surface irrigated land.

Class	Irrigation slope 1/	Cross slope	Possible irrigation water efficiencies	Irrigation operation labor requirement	Method limitations	Leveling requirement
A_1	Uniform but not more than 0.05 percent	None	High	Very low	None	None
A_2	Uniform				Length of level borders is restricted.	
B_1		Uniform but not more than 0.3 percent			Length of level borders restricted. Border widths are restricted.	Leveling desirable to increase length or width of level borders.
B_2		Variable but not more than 0.3 percent		Low		Leveling desirable to reduce labor requirement.
B_3		Either uniform or variable and more than 0.3 percent but not more than 0.5 percent			Border widths are very restricted. Level borders not permissible. Shallow furrows not permissible on coarse or very coarse-textured soils. Corrugations must have down-slope of at least four times cross slope.	
C_1	Fairly uniform - slopes have maximum grades not over twice minimum; concave slopes have maximum grade not over 1 1/2 times minimum. Undulating slopes not permissible.)	Uniform or variable	Good	Moderately low	Level borders not permissible.	Leveling desirable to reduce labor requirement and improve irrigation efficiencies.
C_2		Uniform or variable but not more than 0.5 percent			Border widths are very restricted. Level borders not permissible. Shallow furrows not permissible on coarse or very coarse-textured soils. Corrugations must have down-slope of at least four times cross slope.	
C_3	Either uniform or fairly uniform as defined above	Either uniform or variable and more than 0.5 percent		Moderate to high	Applicable only for contour ditches or to cross slope or contour furrow irrigation within special limitations of furrow depth and soil texture.	
D_1	Variable but without level reaches or reverse grades	Variable but not more than 0.3 percent	Poor	Moderate	Border widths are restricted. Level borders or corrugations not permissible.	Leveling required for conservation irrigation.
D_2		Variable but not more than 0.5 percent		High	Border widths are very restricted. Level borders or corrugations not permissible. Shallow furrows not permissible on coarse or very coarse-textured soils.	
E		Variable and more than 0.5 percent	Very poor	Very high	Applicable only for contour ditches or furrows within special limitations of furrow depth and soil texture.	

1/ Maximum and minimum downfield grades are limited by (1) requirements for drainage, (2) protection from erosion by storm runoff, and (3) the criteria for the irrigation method to be used.

A topographic survey is always helpful and is usually necessary in planning a farm irrigation system. Such surveys may vary from a few scattered shots to a precise grid-type survey. Any of the conventional methods of making this survey are satisfactory, but it is important to locate and map benchmarks and points of known horizontal position in order to reestablish both vertical and horizontal control on the ground.

Prior to leveling design, the farm irrigation system must be planned so that the location of field boundaries, irrigation water-supply system, drains, and field roads are known. The leveling plan for an individual field must provide for furnishing borrow to or for absorbing waste from these adjacent features. It must also provide for the proper ratio between excavation and embankment.

Before leveling, the field should be cleared of trash and vegetative material. In desert areas, sage and brush should be cleared, raked, and burned. On cultivated lands, mowing and raking or burning will usually suffice. Crop ridges should be eliminated by disking or smoothing. The grass on sod lands should be mowed and raked, but the vegetation should not be plowed under immediately prior to leveling. Any operation that leaves the surface in a loosened condition makes it difficult to grade to an exact elevation.

Surveys

Planning Surveys.

A topographic survey often is needed to provide a basis for planning the farm irrigation system. For the layout of contour benches, a survey showing considerable detail is essential. A topographic survey may be made by any of the conventional methods; plane table, transit survey, field cross section, or if construction is to be done immediately, the grid system which will be utilized for construction can be used.

Design and Construction Surveys.

The proper field arrangement and the farm water distribution and drainage system must be planned before the field leveling can be designed. An entire field should be designed and leveled as a unit.

The area should be first cleared of vegetation and the surface prepared for construction. A grid system is usually used to provide both horizontal and vertical control and each grid point is staked. Half or full lath are commonly used for staking. Double right-angle prisms are often useful in staking the grid. The stakes remain in the field and after the leveling job has been designed, are marked to serve for construction stakes. Since they cannot remain in a cultivated field for long, the staking and design is usually done immediately prior to construction.

The usual grid spacing is 100 feet in each direction, but other spacings as 50 x 50, 66 x 66, 50 x 100, 75 x 100, etc., are sometimes found useful. Inexperienced earthmoving operators often have difficulty in carrying elevation 100 feet between stakes and sometimes request a closer spacing. However, a 50 x 50 grid requires four times as many stakes to set, shoot, plot, compute and mark as a 100 x 100-foot-grid, and so the wider spacing should be used where possible.

Many times ridges or swales will be found which fall between grid corners. When this occurs, additional stakes should be set on the highs or lows. These stakes are located in the grid with markings as (E+72) (7+00) and so are often referred to as "plus stakes".

After all points have been staked, levels are run to determine the ground elevation of each. Normally, ground elevations are determined to the nearest tenth foot, but may be taken to the nearest 0.05 foot in level areas or where other conditions make additional refinement helpful. Bench marks are established to the nearest hundredth foot and they also are often used as points of horizontal control. The location and the elevation of the water source is determined and any structures that might affect the drainage system are located and the controlling elevations determined. Any existing pipelines, drains, power lines, structures, roads or other important physical features are similarly located and tied into the grid.

Figure 12-1 shows a grid survey for leveling a 40-acre field using a 100 x 100-foot spacing. For convenience in identification, each east-west line of stakes was lettered and each north-south line was numbered. There are many methods of establishing a grid system on a field but in this case, Line 7 was first established at right angles to the south edge of the field and point A-7 placed one-half grid interval (50 feet) north of the fence line. Lines F and G were then established at right angles to Line 7 and their points chained and staked. Line 8 was then measured and staked parallel to Line 7. The adjacent Lines 7 and 8 were arbitrarily selected since they are near the center of the field.

At this stage, there were two rows of stakes in both directions across the field. Since the work was carefully done, the remaining stakes were placed by eye with sufficient accuracy. Thus, E-6 was placed in line with F-6 and G-6 and E-7 and E-8; E-5 with F-5 and G-5 and E-6, E-7 and E-8; etc.

Elevations of all points were then determined and plotted as shown in figure 12-1.

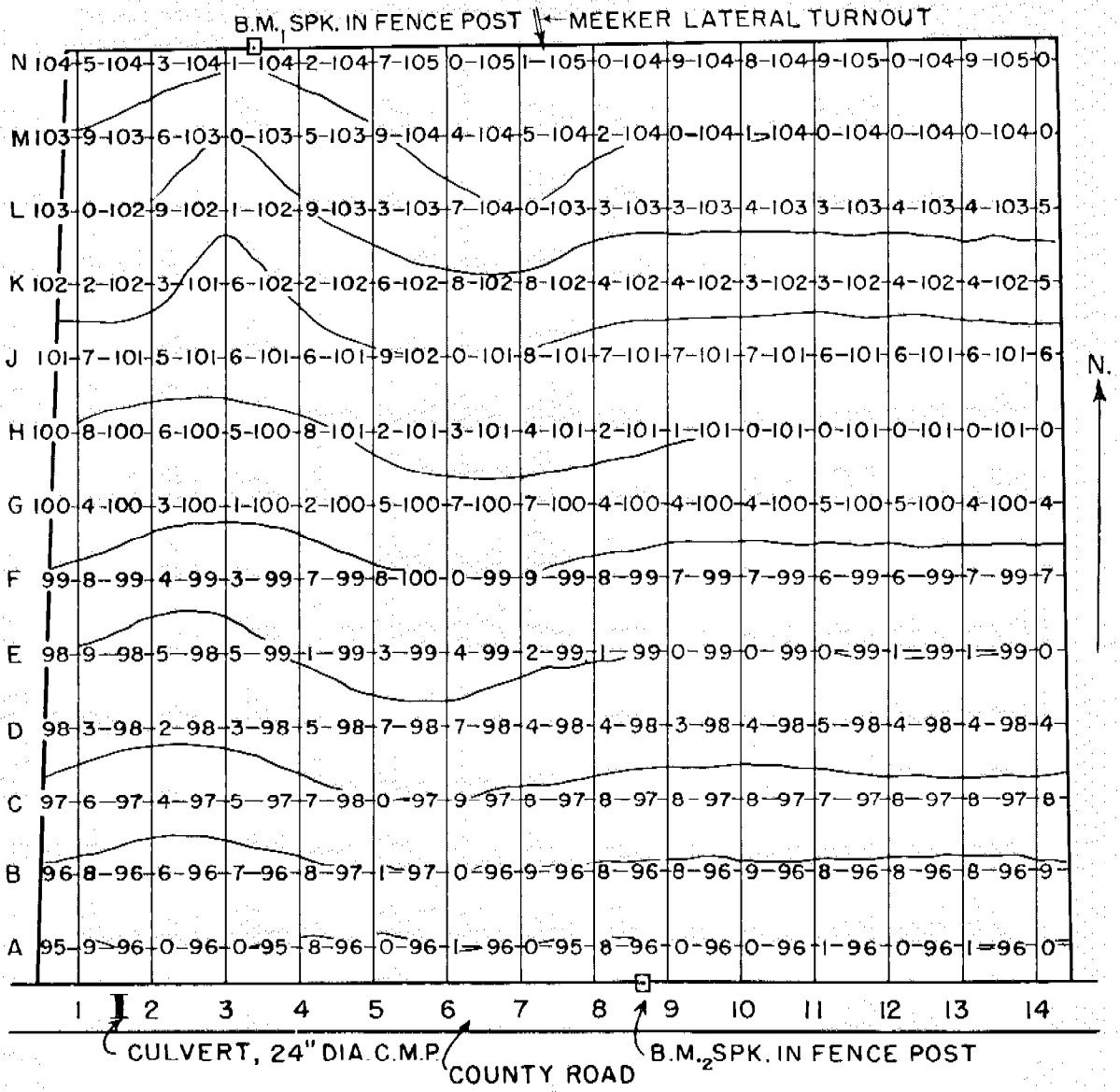


Figure 12-1.--Grid map for land leveling.

Land-Leveling Design Methods

General.
There are four basic methods and a great many variations of each method of land-leveling design in common use. These basic methods are:

1. The plane method.
2. The profile method.
3. The plan-inspection method.
4. The contour-adjustment method.

Each of these has some advantages and disadvantages, but when intelligently used, all will provide satisfactory results.

The Plane Method.

The plane method is so called because the resulting land surface has a uniform downfield slope and a uniform cross slope. Thus, a true plane surface results. It is a very useful method for developing Class A_1, A_2, and B_1 surface relief and is widely used.

The centroid of the area is first found, and a plane is passed through that point at an elevation equal to the average elevation of the field. When this is done, regardless of the slope of the plane, the volume of excavation equals the volume of fill. Since, as will be discussed later, more excavation than fill is necessary, the plane is lowered sufficiently to provide a proper balance.

The procedure for the design of land leveling by the plane method follows:

Subdivide the field into subareas.—The topography of many fields is such that they cannot be economically leveled to a single plane. Here, divide the field into parts, each of which can be developed to a plane surface. In making these subdivisions, keep in mind that the quality of the leveling job may be inadequate if the subareas do not match with the proposed ditch or water-supply locations. A study of the irrigation plan, the topographic map, and down-field profiles will assist the engineer in properly locating the subdivision boundaries.

Figure 12-2 is an example of a field that has been broken into three subareas for leveling. Here, the profiles and topographic map were both used as a guide. Each subarea is then considered as a separate field except that the common boundaries of the subareas are integrated into the design of the adjacent subarea.

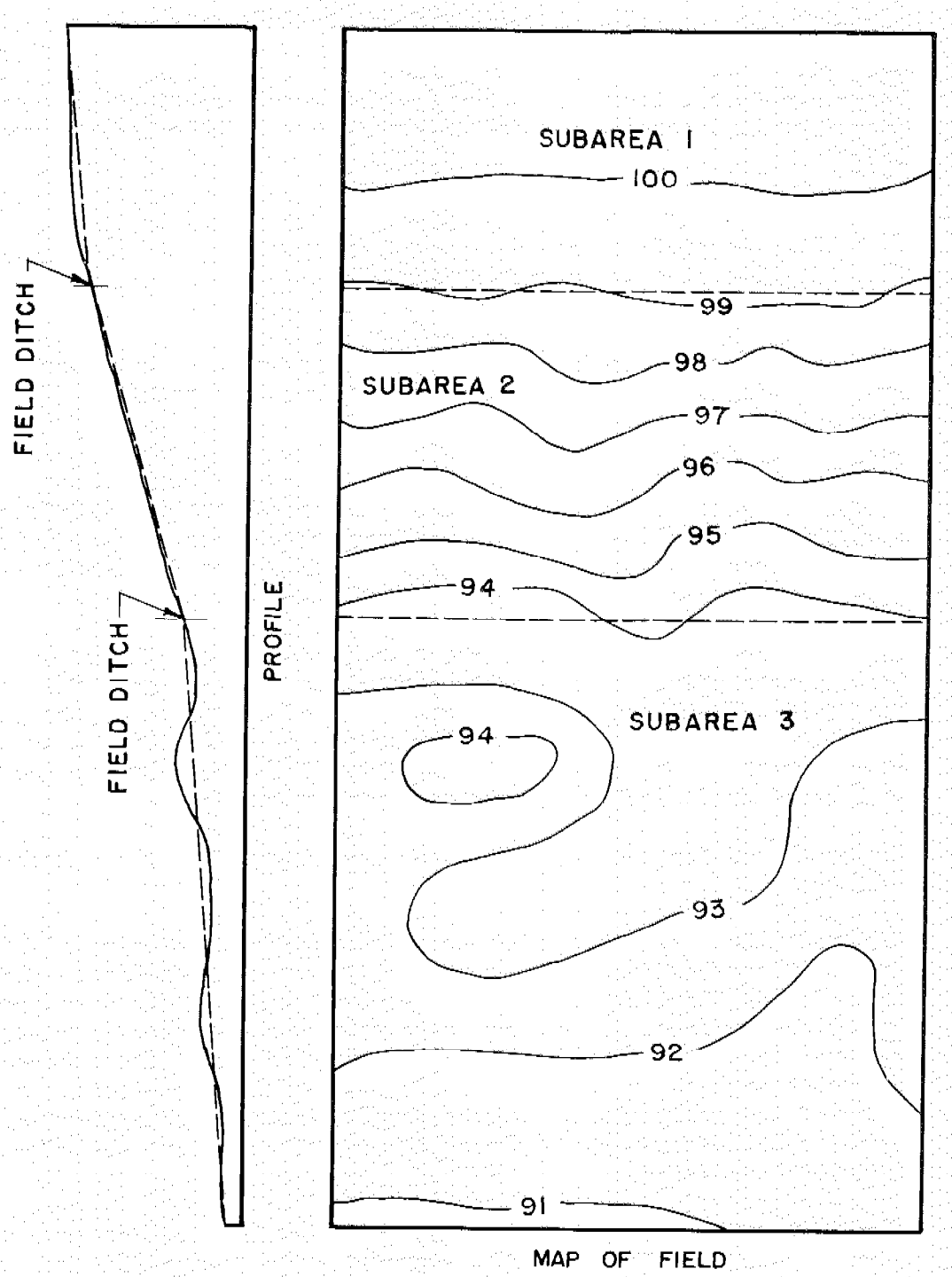


Figure 12-2.--Field subdivision for leveling.

Locate the centroid.—The centroid of a rectangular field is located at the intersection of its diagonals. The centroid of a triangular field is located at the intersection of lines drawn from its corners to the midpoints of the opposite sides.

Irregular fields may be divided into triangles and rectangles or into rectangles alone, and the distance to the centroid of the field from any line of reference is equal to the sum of the products obtained by multiplying the area of each part times the distance from the line of reference to its centroid, divided by the area of the entire field. By computing the distance to the centroid from [redacted] points of the centroid can be determined.

The centroid can also be located with sufficient accuracy by assuming that each stake (ignoring "plus stakes") in the field represents the same area. Figure 12-3 shows how the centroid can be located in this manner.

Assuming a line of reference 100 feet south of line A, the number of stakes in each line multiplied by the distance (in stations) from the reference line is:

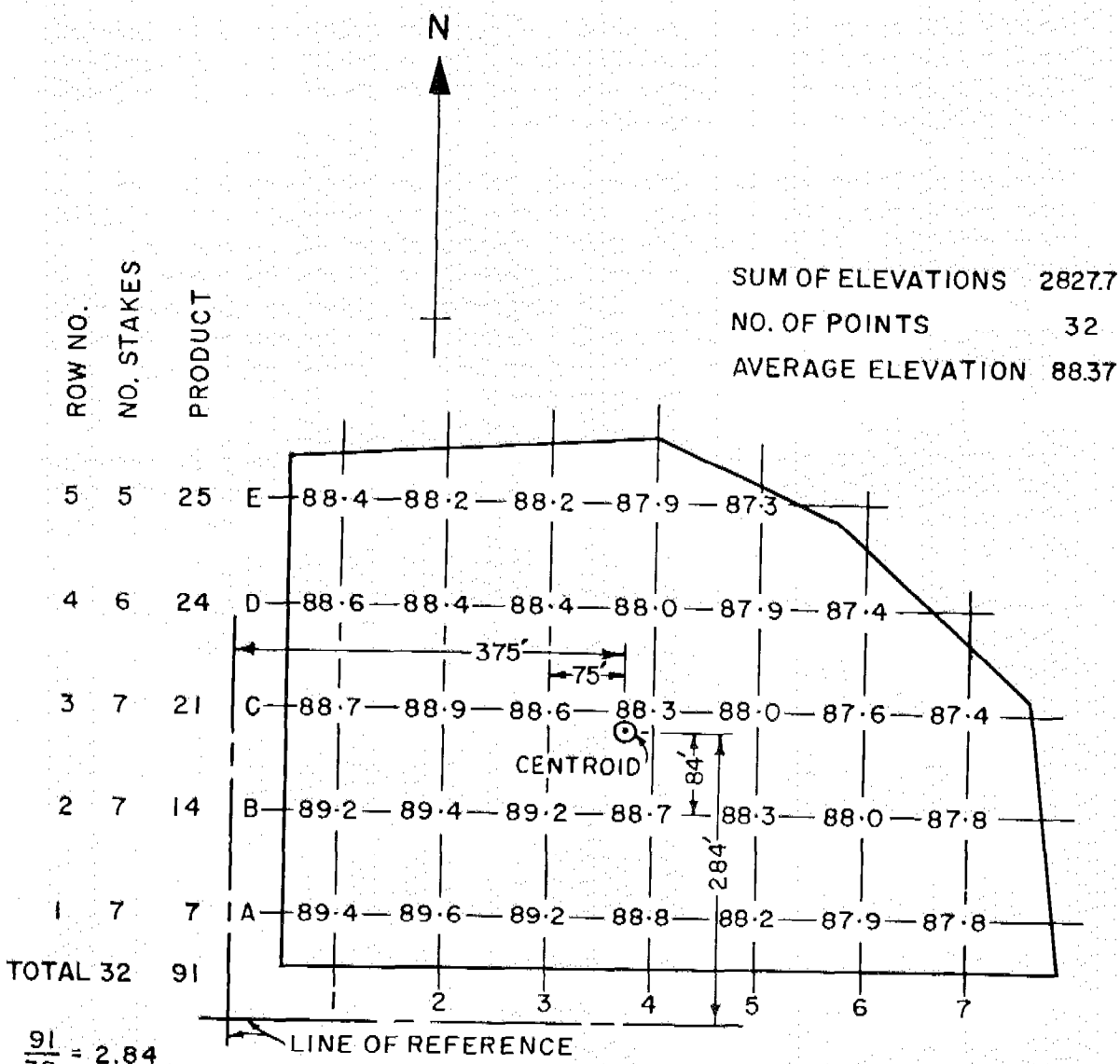
Line	Distance	No. of stakes	Product
E	5 stations	5	25
D	4	6	24
C	3	7	21
B	2	7	14
A	1	7	7
	Total	32	91

The distance of the centroid from the reference line is then found by dividing the sum of the products by the total number of stakes or

$$\frac{91}{32} = 2.84 \text{ stations or } 284 \text{ feet}$$

The centroid is, therefore, 284 feet from the reference line, or 84 feet north of line B.

Another line of reference was assumed to be 100 feet west of line 1 and the location of the centroid in an east-west direction computed the same way. With the two dimensions, the point was located at (B+84) and (3+75).



$\frac{91}{32} = 2.84$

ROW NO.	1	2	3	4	5	6	7	TOTAL
NO STAKES	5	5	5	5	5	4	3	32
PRODUCT	5	10	15	20	25	24	21	120

$\frac{120}{32} = 3.75$

Figure 12-3.--Location of the centroid of a field.

If the field is nearly rectangular, such as shown on figure 12-4, the centroid is located at the intersection of the diagonals or at coordinate (G+00) (7+50).

Determine the average elevation of the field.—Obtain the average elevation of the field by adding the elevations at all the grid corners in the field and dividing the sum by the number of points. Thus, for figure 12-3 the total of the 32 elevations on the grid corners is 2,827.7. The average elevation is

$$\frac{2827.7}{32} = 88.37$$

Any plane passing through the centroid at this elevation will produce equal volumes of cut and fill. Similarly, in the example on figure 12-4 the sum of the elevations of the 182 grid points on the field is 18,271.3 so the average elevation is

$$\frac{18,271.3}{182} = 100.39$$

Compute the slope of the plane of best fit.—Omit this computation if it is obvious from the topography that the plane of best fit will not meet leveling criteria.

With grid points at 100-foot centers, it can be shown that the slope of the plane of best fit on a rectangular area is expressed by the following

$$M_x = \frac{\sum (D_x H_y) - (A)(H)}{B}$$

$$M_y = \frac{\sum (D_y H_x) - (A)(H)}{B}$$

Y AXIS — X AXIS — TURNOUT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	H_x	D_y	$(H_x D_y)$
N	104.5	104.3	104.1	104.2	104.7	105.0	105.1	105.1	104.9	104.8	104.9	105.0	104.9	105.0	1466.4	1	1466.4
M	103.9	103.6	103.0	103.5	103.9	104.4	104.5	104.2	104.0	104.1	104.0	104.0	104.0	104.0	1455.1	2	2910.2
L	103.0	102.9	102.1	102.9	103.3	103.7	104.0	103.3	103.3	103.4	103.3	103.4	103.4	103.5	1445.5	3	4336.5
K	102.2	102.3	101.6	102.2	102.6	102.8	102.8	102.4	102.4	102.3	102.3	102.4	102.4	102.5	1433.2	4	5732.8
J	101.7	101.5	101.6	101.6	101.9	102.0	101.8	101.7	101.7	101.7	101.6	101.6	101.6	101.6	1423.6	5	7118.0
H	100.8	100.6	100.5	100.8	101.2	101.3	101.4	101.2	101.1	101.0	101.0	101.0	101.0	101.0	1413.9	6	8483.4
G	100.4	100.3	100.1	100.2	100.5	100.7	100.7	100.4	100.4	100.4	100.5	100.5	100.4	100.4	1405.9	7	9841.3
F	99.8	99.4	99.3	99.7	99.8	100.0	99.9	99.8	99.7	99.7	99.6	99.6	99.7	99.7	1395.7	8	11165.6
E	98.9	98.5	98.5	99.1	99.3	99.4	99.2	99.1	99.0	99.0	99.0	99.1	99.1	99.0	1386.2	9	12475.8
D	98.3	98.2	98.3	98.5	98.7	98.7	98.4	98.4	98.3	98.4	98.5	98.4	98.4	98.4	1377.9	10	13779.0
C	97.6	97.4	97.5	97.7	98.0	97.9	97.8	97.8	97.8	97.8	97.7	97.8	97.8	97.8	1368.4	11	15052.4
B	96.8	96.6	96.7	96.8	97.1	97.0	96.9	96.8	96.8	96.9	96.8	96.8	96.8	96.9	1355.7	12	16268.4
A	95.9	96.0	96.0	95.8	96.0	96.1	96.0	95.8	96.0	96.0	96.1	96.0	96.1	96.0	1343.8	13	17469.4
															ΣH_x=1,8271.3		$\Sigma(H_x D_y)$ =126,099.2

CULVERT, 24" DIA. C.M.P. (at 2) — COUNTY ROAD (at 7)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
H_y	1303.8	1301.6	1299.3	1303.0	1307.0	1309.0	1308.5	1305.9	1305.4	1305.5	1305.3	1305.6	1305.6	1305.8	ΣH_y =1,8271.3
D_x	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
$(H_y D_x)$	1303.8	2603.2	3897.9	5212.0	6535.0	7854.0	9159.5	10447.2	11748.6	13055.0	14358.3	15667.2	16972.8	18281.2	$\Sigma(H_y D_x)$ =137,095.7

$$M_y = \frac{\Sigma(H_x D_y) - A(\Sigma H_x)}{B}$$

$$= \frac{126{,}099.2 - (7)(18{,}271.3)}{2548.0}$$

$$= -0.706 \text{ PERCENT}$$

$$M_x = \frac{\Sigma(H_y D_x) - A(\Sigma H_y)}{B}$$

$$= \frac{137{,}095.7 - (7.5)(18{,}271.3)}{2957.5}$$

$$= 0.0206 \text{ PERCENT}$$

$$\text{AV. EL.} = \frac{18{,}271.3}{13 \times 14}$$

$$= 100.39$$

Figure 12-4.—Determination of plane of best fit.

where D_x = distance in stations from the y axis.

D_y = distance in stations from the x axis.

H = sum of the elevations at all grid points.

H_x = sum of the elevations in an x direction along a grid line.

H_y = sum of the elevations in a y direction along a grid line.

M_x = slope of the plane in the x direction.

M_y = slope of the plane in the y direction.

A = constants taken from table 12-2.

B = constants taken from table 12-2.

If grid points are at other than 100-foot centers, the slopes M_x and M_y as determined by the preceding formula must be corrected as follows:

$$\text{Corrected } M_x = \frac{\text{Spacing of grid points in X direction}}{100} M_x$$

$$\text{Corrected } M_y = \frac{\text{Spacing of grid points in Y direction}}{100} M_y$$

An example of this calculation is shown in figure 12-4.

1. The sums of the elevations on each line were computed thus on the N line,

$$H_x = 104.5 + 104.3 + 104.1 + 104.2 + 104.7 + 105.0 + 105.1 + 105.0 + 104.9 + 104.8 + 104.9 + 105.0 + 104.9 + 105.0 = 1{,}466.4$$

Similarly on the 5 line.

$$H_y = 104.7 + 103.9 + 103.3 + 102.6 + 101.9 + 101.2 + 100.5 + 99.8 + 99.3 + 98.7 + 98.0 + 97.1 + 96.0 = 1{,}307.0$$

2. The value of H was computed by adding all the values of H_x. This sum was 18,271.3. As a check, the values of H_y were added and the same total obtained.

3. The location of the x and y axes were assumed. In this problem the x axis was placed one station north of line N and the y axis was placed one station west of line 1.

4. Values of D_y and D_x were tabulated. Since the N line is one station from the x axis, the value of D_y for the N line is 1; similarly, D_y for the M is 2; etc.

5. The products of $(H_x D_y)$ and $(H_y D_x)$ for each line were computed and tabulated as shown.

Table 12-2.--Constants for determination of plane of best fit.

NUMBER OF STATIONS IN THE DIRECTION SLOPE OF BEST FIT IS BEING DETERMINED

NUMBER OF STATIONS TRANSVERSE TO THE DIRECTION SLOPE OF BEST FIT IS BEING DETERMINED	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	VALUES OF A																								
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5
	VALUES OF B																								
1	0.5	2	5	10	17.5	28	42	60	82.5	110	143	182	227.5	280	340	408	484.5	570	665	770	885.5	1012	1150	1300	1462.5
2	1.0	4	10	20	35	56	84	120	165	220	286	364	455	560	680	816	969	1140	1330	1540	1771	2024	2300	2600	2925
3	1.5	6	15	30	52.5	84	126	180	247.5	330	429	546	682.5	840	1020	1224	1453.5	1710	1995	2310	2656.5	3036	3450	3900	4387.5
4	2.0	8	20	40	70	112	168	240	330	440	572	728	910	1120	1360	1632	1938	2280	2660	3080	3542	4048	4600	5200	5850
5	2.5	10	25	50	87.5	140	210	300	412.5	550	715	910	1137.5	1400	1700	2040	2422.5	2850	3325	3850	4427.5	5060	5750	6500	7312.5
6	3.0	12	30	60	105	168	252	360	495	660	858	1092	1365	1680	2040	2448	2907	3420	3990	4620	5313	6072	6900	7800	8775
7	3.5	14	35	70	122.5	196	294	420	577.5	770	1001	1274	1592.5	1960	2380	2856	3391.5	3990	4655	5390	6198.5	7084	8050	9100	10237.5
8	4.0	16	40	80	140	224	336	480	660	880	1144	1456	1820	2240	2720	3264	3876	4560	5320	6160	7084	8096	9200	10400	11700
9	4.5	18	45	90	157.5	252	378	540	742.5	990	1287	1638	2047.5	2520	3060	3672	4360.5	5130	5985	6930	7969.5	9108	10350	11700	13162.5
10	5.0	20	50	100	175	280	420	600	825	1100	1430	1820	2275	2800	3400	4080	4845	5700	6650	7700	8855	10120	11500	13000	14625
11	5.5	22	55	110	192.5	308	462	660	907.5	1210	1573	2002	2502.5	3080	3740	4488	5329.5	6270	7315	8470	9740.5	11132	12650	14300	16087.5
12	6.0	24	60	120	210	336	504	720	990	1320	1716	2184	2730	3360	4080	4896	5814	6840	7980	9240	10626	12144	13800	15600	17550
13	6.5	26	65	130	227.5	364	546	780	1072.5	1430	1859	2366	2957.5	3640	4420	5304	6298.5	7410	8645	10010	11511.5	13156	14950	16900	19012.5
14	7.0	28	70	140	245	392	588	840	1155	1540	2002	2548	3185	3920	4760	5712	6783	7980	9310	10780	12397	14168	16100	18200	20475
15	7.5	30	75	150	262.5	420	630	900	1237.5	1650	2145	2730	3412.5	4200	5100	6120	7267.5	8550	9975	11550	13282.5	15180	17250	19500	21937.5
16	8.0	32	80	160	280	448	672	960	1320	1760	2288	2912	3640	4480	5440	6528	7752	9120	10640	12320	14168	16192	18400	20800	23400
17	8.5	34	85	170	297.5	476	714	1020	1402.5	1870	2431	3094	3867.5	4760	5780	6936	8236.5	9690	11305	13090	15053.5	17204	19550	22100	24862.5
18	9.0	36	90	180	315	504	756	1080	1485	1980	2574	3276	4095	5040	6120	7344	8721	10260	11970	13860	15939	18216	20700	23400	26325
19	9.5	38	95	190	332.5	532	798	1140	1567.5	2090	2717	3458	4322.5	5320	6460	7752	9205.5	10830	12635	14630	16824.5	19228	21850	24700	27787.5
20	10.0	40	100	200	350	560	840	1200	1650	2200	2860	3640	4550	5600	6800	8160	9690	11400	13300	15400	17710	20240	23000	26000	29250
21	10.5	42	105	210	367.5	588	882	1260	1732.5	2310	3003	3822	4777.5	5880	7140	8568	10174.5	11970	13965	16170	18595.5	21252	24150	27300	30712.5
22	11.0	44	110	220	385	616	924	1320	1815	2420	3146	4004	5005	6160	7480	8976	10659	12540	14630	16940	19481	22264	25300	28600	32175
23	11.5	46	115	230	402.5	644	966	1380	1897.5	2530	3289	4186	5232.5	6440	7820	9384	11143.5	13110	15295	17710	20366.5	23276	26450	29900	33637.5
24	12.0	48	120	240	420	672	1008	1440	1980	2640	3432	4368	5460	6720	8160	9792	11628	13680	15960	18480	21252	24288	27600	31200	35100
25	12.5	50	125	250	437.5	700	1050	1500	2062.5	2750	3575	4550	5687.5	7000	8500	10200	12112.5	14250	16625	19250	22137.5	25300	28750	32500	36562.5
26	13.0	52	130	260	455	728	1092	1560	2145	2860	3718	4732	5915	7280	8840	10608	12597	14820	17290	20020	23023	26312	29900	33800	38025

6. The sum of the products (H_xD_y) were obtained; this value is $\sum (H_xD_y)$. $\sum (H_yD_x)$ was also computed.

7. Values of A and B were taken from table 12-2. Thus, for the slope in the direction of the y axis, the number of stations along the y axis is 13, and this value was found on the horizontal column at the top of the table. Directly below, A was found to be 7.0. Since the number of stations along the x axis is 14, going down the same column to a point opposite 14 on the left side, the value of B was found to be 2548. Similarly, for the slope in the direction of the x axis, A is found to be 7.5 and B equals 2957.5.

8. These figures are substituted in the equation, and

$$M_y = -0.706 \text{ percent}$$

$$M_x = 0.020 \text{ percent}$$

Note that M_y is negative. That means that the elevation of the plane reaches a lower elevation as the distance from the x axis increases. Since M_x is positive, the plane of best fit rises to the right. It also should be noted that since the units of distance (D_x and D_y) were in stations, the result is in feet per station or percent slope.

Determine the elevation of the plane at the centroid.—Any plane passing through the centroid at the average elevation as previously determined will produce equal volumes of excavation and embankment. However, as explained in more detail in Earthwork Balance, it is necessary to have a larger volume of cut than fill to obtain a balance. Attain this by lowering the whole field a few hundredths of a foot. This will increase the amount of excavation and reduce the fill required.

The field in figure 12-4 has an average elevation of 100.39. To provide extra excavation the whole field is lowered 0.04 foot or to elevation 100.35 at the centroid.

It often is desirable to provide for borrow from a field to construct farm roads or elevated ditches or to waste spoil from a drain on a field. In these instances, the elevation of the centroid may be further raised or lowered as computed by the following formula:

$$H = \frac{27V}{A}$$

where

H = the adjustment necessary in feet (Positive when earth is to be brought onto the fill and negative when earth is removed)

V = the volume of borrow or waste in cubic yards

A = the area of the field in square feet

Had it been necessary to borrow 600 cubic yards from the field on figure 12-4, the following computation would have been made:

A = Average length of field x average width of field
= 1,373 x 1,275 = 1,750,575 square feet.

$$H = \frac{27 \times 600}{1,750,575} = 0.01$$

Average elevation of field	100.39
Less shrinkage	-0.04
Less borrow	-0.01
Design elevation of centroid	100.34

Compute the elevation for each grid point.—With the elevation of the centroid known and the downfield grade and cross slope selected, compute the elevation of each grid point.

In figure 12-5 the same field shown in figure 12-1 and figure 12-4 has been designed for leveling to the plane of best fit without either borrow or waste.

The following is known:

Location of centroid	(G+00) (7+50)
Elevation of centroid	100.35
Downfield slope	-0.706 percent
Cross slope	+0.020 percent

The elevation of point (G+00) (8+00) is then

$$100.35 + 1/2\ (0.02) = 100.36$$

and the elevation of all other grid points on line G can be computed by adding or subtracting 0.02 for each grid point to the right or left respectively.

The elevations of line H can then be obtained by adding 0.706 foot to the proposed elevations on line G. Similarly, all of the elevations are determined.

Compute the cuts and fills.—The desired cut or fill can be computed from a comparison of the original and the proposed elevations. Although the proposed elevations are carried to hundredths of a foot, round the cuts or fills to the nearest tenth or half tenth.

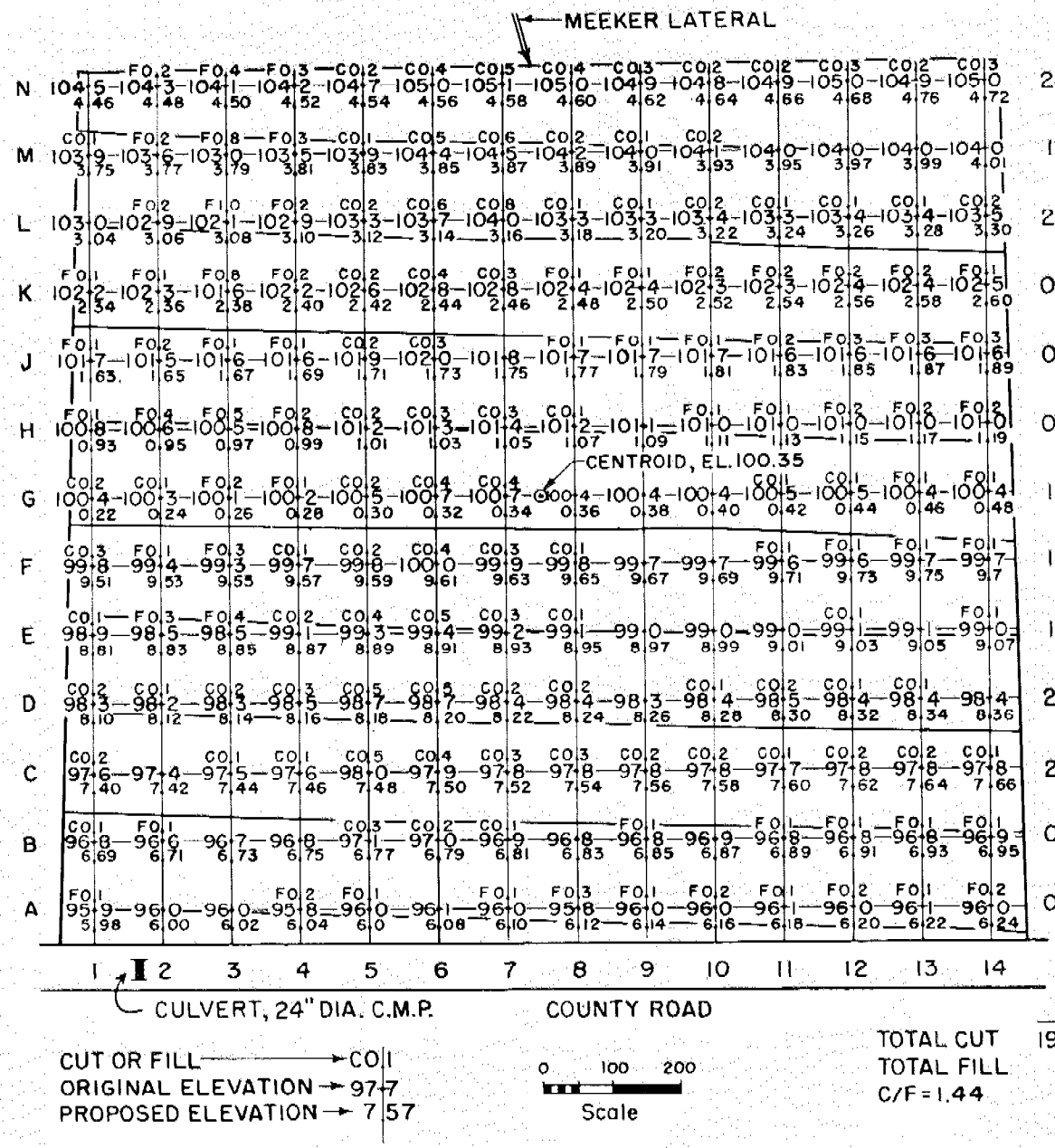


Figure 12-5.--The plane method of land leveling.

The calculations can be checked by determining the variation per stake. This variation should be less than 0.005 foot since the proposed elevations were rounded to the nearest hundredth foot. To do this, the cuts and fills on the computed points are separately summed and the difference between the two compared with the product of the shrinkage adjustment and the number of stakes. Thus

Sum of the cuts	=	20.6
Sum of the fills	=	14.1
Difference		6.5

No. of stakes = 13 x 14 = 182
Shrinkage adjustment = 182 x 0.04' = 7.28

Total variation = 7.28 - 6.5 = 0.78

Variation per stake = 0.78/182 = 0.0043

Since the variation per stake is less than 0.005, it is probable that the calculations are correct. Note that in the above example, the cuts and fills are <u>not</u> weighted for the area they represent as is done for the determination of the earthwork balance. Then check the earthwork balance as described in the section on Earthwork Calculation and make final adjustments to obtain the correct cut/fill ratio.

<u>The Profile Method</u>.
The profile method is so called because the designer works with profiles of the grid lines rather than with elevations as plotted on a map. It is especially well adapted to leveling design for very flat lands or land with undulating topography on which it is desired to develop a surface relief of Class B_2, C_1 or C_2.

There are many variations of the profile method, but essentially it consists of a trial and error method of adjusting grades on plotted profiles until the irrigation criteria are met and an earthwork balance is attained. Many workers find it relatively easy to select grades on a profile that will provide balanced cut and fill with reasonably short-haul distance and so the method is widely used.

Plot the profiles.--The profiles are commonly plotted in one direction and the individual profiles so located on the paper that the datum line for each profile is horizontally located in the correct position with the datum lines of adjacent profile. Figure 12.6 is an example of the same field shown in figure 12.1 plotted in this manner. It should be noted that the distance between the datum lines of line A and line B is identical with the distance between line 1 and line 2 on the A profile.

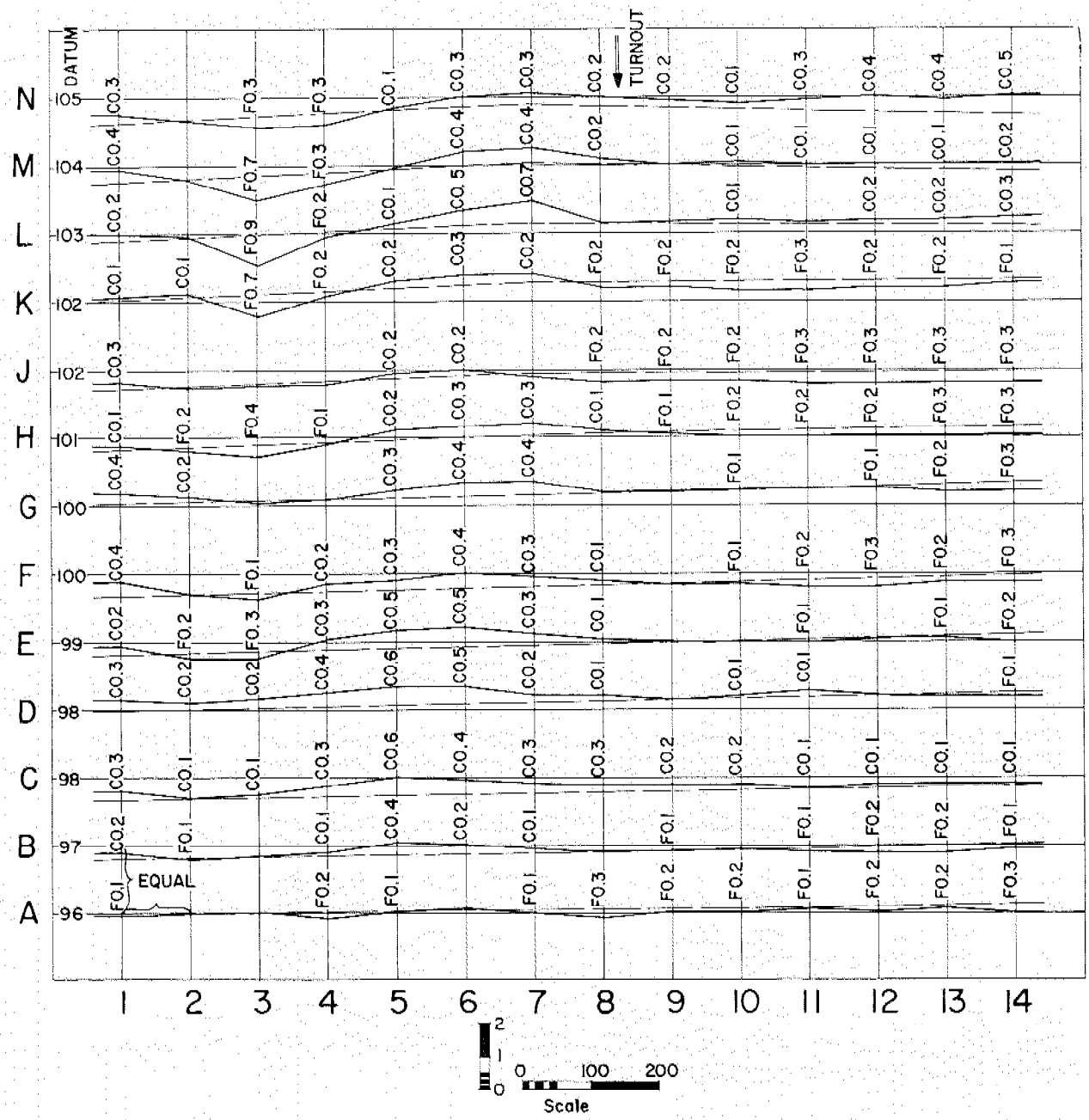


Figure 12-6.—The profile method of land leveling.

Figure 12.6 was plotted with the profiles across the slope. Some workers prefer to plot the profiles down the slope. Figure 12.7 is the same field with a down-field plot. Either method is satisfactory.

It sometimes is helpful to plot profiles in both directions, and it is quite common to plot at least a few key profiles in the opposite direction from the regular plot. These profiles often are drawn on the same sheet directly over but at right angles to the principal plot.

Another variation of plotting is the "two way plot" as shown on figure 12.8. The advantage of this method is that it provides a three-dimensional picture of the land surface, which is sometimes useful to those who are infrequently called upon for land-leveling design. In this method of plotting, the datum elevation is below the lowest elevation of the field, and each point is plotted both above the datum and to the right of the point of reference. All of the diagonals are 45 degrees. The "two way plot" cannot conveniently be used on fields with considerable differences in elevation.

Establish trial gradelines.—Trial gradelines are established on each profile based on the irrigation plan and the leveling criteria. On figures 12.6 and 12.7 it was decided to carry ditches to both the left and right from the turnout and to supply a cross ditch on the G line by carrying the water down the right side of the field. The water surface at the turnout is El. 105.5, and the field at that point should be at least 0.5 foot lower. Because of drainage requirements, it was further decided that the A line should have a slight grade downward to the left. Drainage criteria for the area should be consulted to determine the maximum and minimum allowable grades for surface drains.

As an example, in figure 12.6, trial gradelines were first placed on the control lines, N, G, and A, and then a balance between cut and fill was approximated by eye by maintaining the proper ratio between the area of cut and the area of fill.

Trial gradelines were then plotted on the other profiles. A smooth transition in cross slope was maintained by making the rate of change of cross slope between profiles equal.

Examine the grades between profiles.—The profiles should then be examined as to the relative elevations of one to another. Do this by plotting the elevations of the trial gradelines in the opposite direction to the original plot; i.e., if the original plot was cross-field, plot the elevations from the trial gradelines down field or vice versa.

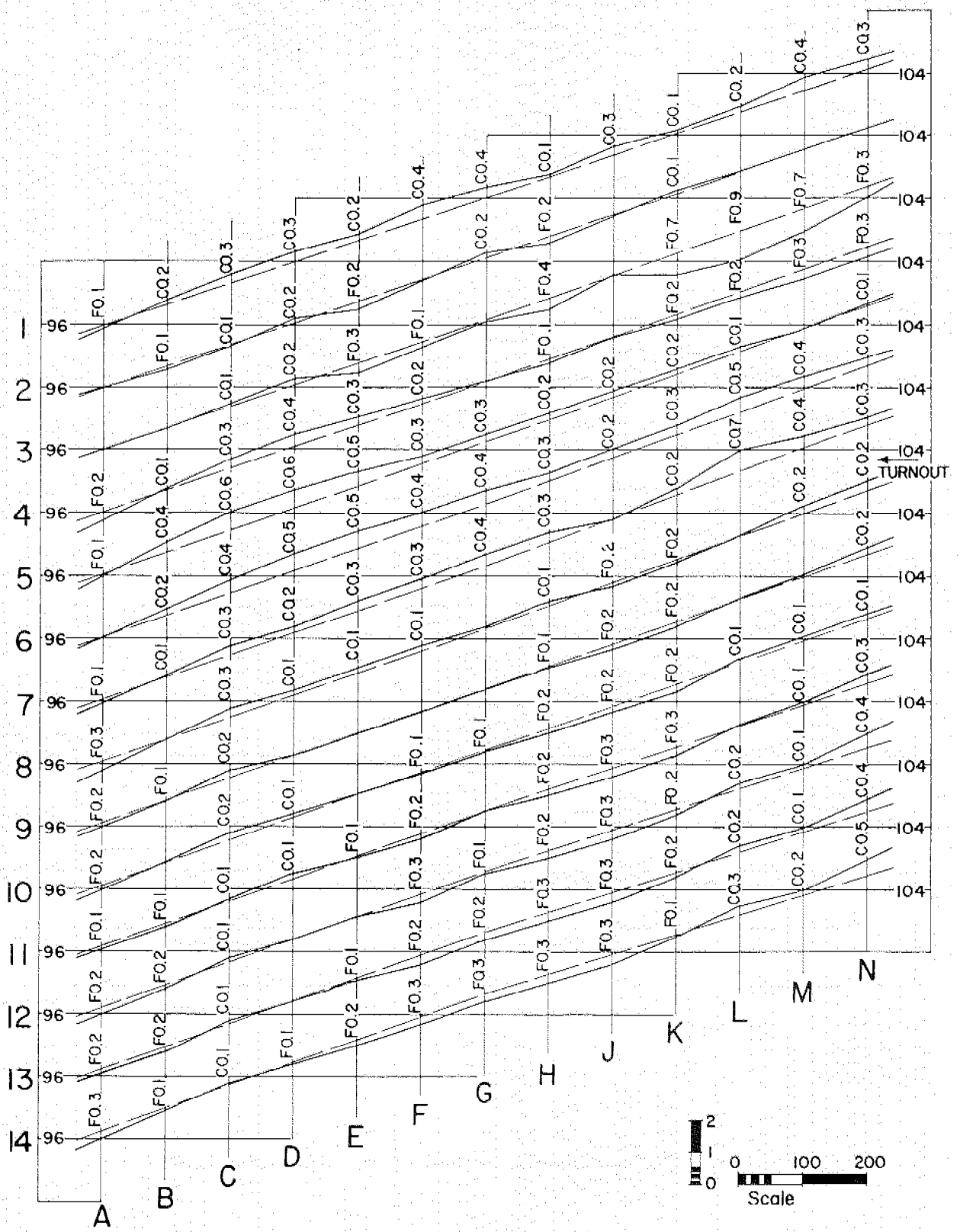


Figure 12-7.—The profile method of land leveling.

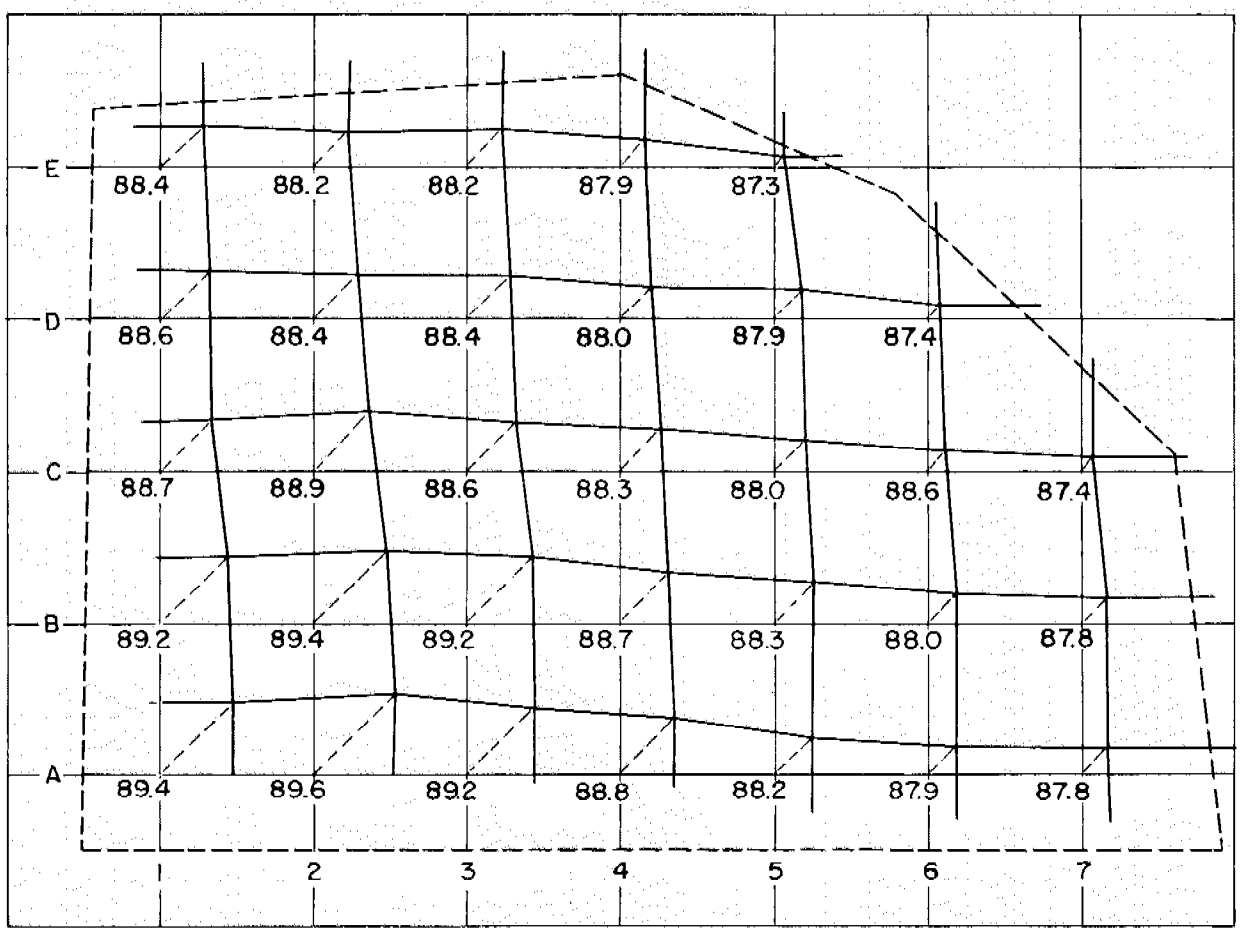


Figure 12-8.--Two-way method of plotting profiles.

Examine this cross profile and if the grade is not uniform to a point where it meets the criteria, draw a revised line. Transfer the elevations from this revised line back to the original profiles and move the gradelines upward or downward as required.

Some workers prefer to adjust the trial gradelines by inspection instead of plotting a cross profile. This is easily done but remember that the total amount the trial gradelines are moved upward must be equaled by the total amount the other lines are moved downward.

This latter procedure was used on figure 12-6. The difference in elevations between adjacent trial gradelines on line 7 was noted, and adjusted by [illegible] the difference [illegible] equal [illegible]. The final gradelines as shown were then drawn.

Regardless of the method, usually several trials are necessary before a satisfactory set of gradelines are developed.

Compute the cuts and fills.—From an inspection of the original and proposed profiles, the cut or fill at each grid point can be determined.

Compute the balance between cut and fill using the summation method as described in Earthwork Calculations. If the balance is not satisfactory, make further adjustment to the profiles until the proper balance is obtained.

The Plan-Inspection Method.

The plan-inspection method is one of the most widely used methods for developing lands to other than Class A or B surface relief. It is similar to the profile method in that it is a trial and error method.

Because of many factors which must be simultaneously considered, it requires considerable judgment to produce a satisfactory land surface without excessive cost. It is, however, widely used by experienced personnel in those areas where land leveling is a major practice. It is especially adapted for use on rolling lands or on fields where it is necessary to use warped surfaces.

In the plan inspection method, the survey data are plotted in the form shown in figure 12.1. Down-field and cross-slope limitations are determined, and by trial and error, proposed elevations are selected which will meet these limitations. In selecting elevations, the designer must simultaneously consider down-field slope, cross slope, earthwork balance, and haul distance.

Figure 12-9 is an example of the use of this method. In developing the design on this field, the following limitations were assumed:

1. Maximum cross slope is 0.1 foot per station and may be variable.
2. Maximum down-field slope is 1.0 foot per station.
3. Down-field slopes may be variable, but on convex slopes maximum grade may not exceed twice the minimum grade; on concave slopes maximum grades may not exceed 1.5 times the minimum grade; undulating slopes are not permissible.
4. The ratio between cut and fill shall be 1.5 ± 0.05.

Other considerations which affected the design were:

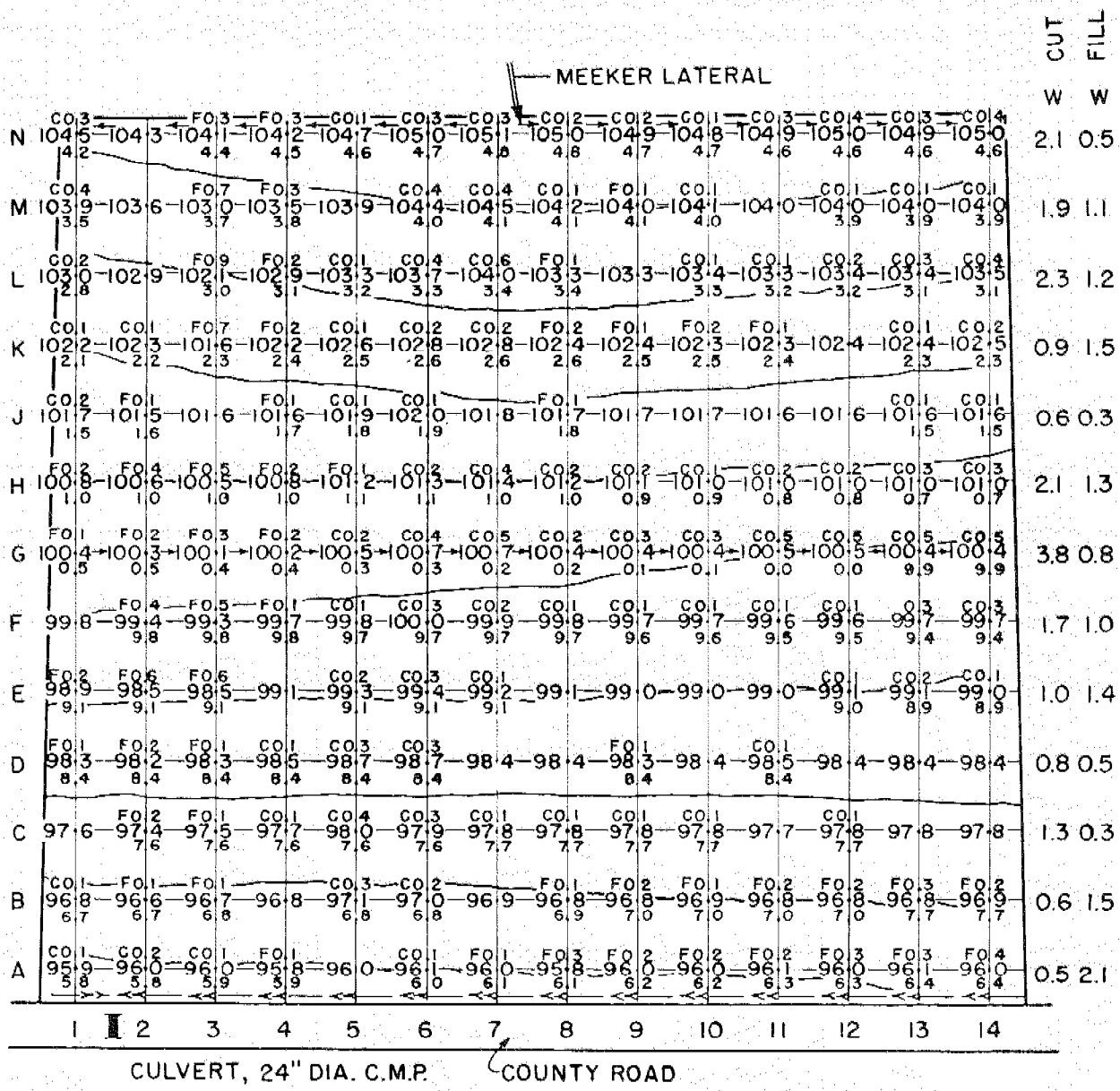
1. The length of run will be broken on the G line with an additional ditch.
2. Because of existing structures the supply lateral will be on the west side.
3. Surface drainage to the road culvert is desired without reverse flow in the drain.
4. The soil will permit a maximum excavation of 1.0 foot.

In developing this plan, elevations were first tentatively selected for the N line so that a ditch could be run in both directions from the turnout. The designer also examined the elevation of the water surface, which was given on figure 12-1 as 105.5, to be sure that the selected high point was not too high to receive service. Usually a minimum head of 0.5 foot is required for irrigation from ditches. Therefore the elevation of N-7 and N-8 could not exceed 105.0.

Tentative elevations were then assigned to the G line to be sure that the ditch to be located on that line would have the proper fall. Similarly, elevations were assigned to the A line to assure drainage.

With the N, G, and A lines serving as controls, elevations for intermediate points were selected by inspection keeping the design criteria in mind. To assure an earthwork balance, a running total of the sum of the tenths cut and tenths fill on each line were carried on the right side of the sheet. Lines N, G, and A, as well as intermediate points, were adjusted upward or downward as necessary to provide an earthwork balance. The designer also considered the borrow that would be required to build a permanent farm lateral on the north end of the field and the excavation that would be produced by the drain on the south.

By trial and error, adjustments were made till the plan on figure 12-9 evolved. This plan satisfies all the established criteria. The surface relief as developed is Class C_1.



EARTHWORK	EXCAVATION	FILL
LATERAL		262
LEVELING	6,690	4,519
DRAIN	407	
TOTAL	7,097	4,841
	C/F = 1.47	

TOTAL CUT = 19.5
TOTAL FILL = 13.5
C/F = 1.44

Figure 12-9.--The plan-inspection method of land leveling.

The Contour-Adjustment Method.
Basically, the contour-adjustment method of land leveling consists of a trial and error adjustment of the contour lines on a plan map. Cuts and fills are then determined by a comparison of the original and proposed contours.

The contour-adjustment method is a convenient method to use on fields where the cross slope can be made uniform across the field. It is especially adapted to those conditions when the leveling is accomplished over a period of time and when stakes cannot be maintained in the field.

It is also useful in leveling lands to be irrigated by contour methods, in leveling between terraces, or in removing extreme ridges or swales from steep lands which are being irrigated by the contour-ditch method.

The contour-adjustment method demands considerable judgment on the part of the designer to keep earth volumes and haul to a minimum. Like the profile method and plan-inspection method, success in its use is dependent upon the ability of the designer to recognize the relative importance of all the factors involved and to select a solution which satisfies the criteria and requires the least earthwork.

A requirement of this system is an accurate contour map of the area to be leveled. This need not necessarily be made with a grid-type survey but adequate ties and bench marks must have been located so that any point on the map can be located in the field through either vertical or horizontal control.

Figure 12-10 is an example of this method of leveling. In this field, the following limitations were assumed:

1. The maximum cross slope is to be 0.3 foot per station.
2. Down-field slopes are to be "fairly uniform" as defined in table 12-1.
3. The soils are deep and cuts up to 2.0 feet are permissible.
4. The field is to be irrigated from field ditches.

In developing this plan, it was obvious that the direction of irrigation should be from north to south. It was also apparent that the use of the maximum allowable cross slope would permit design with minimum earthwork quantities.

The location of the water supply at the northeast corner of the field requires that fall be provided to the west for the irrigation ditch along the north edge of the field. To provide this, the contour lines on the upper edge of the field were run in a north westerly direction. Likewise since it was not planned to change the natural drainage outlet for the field, the contours were arranged along the south line to provide drainage to the outlet.

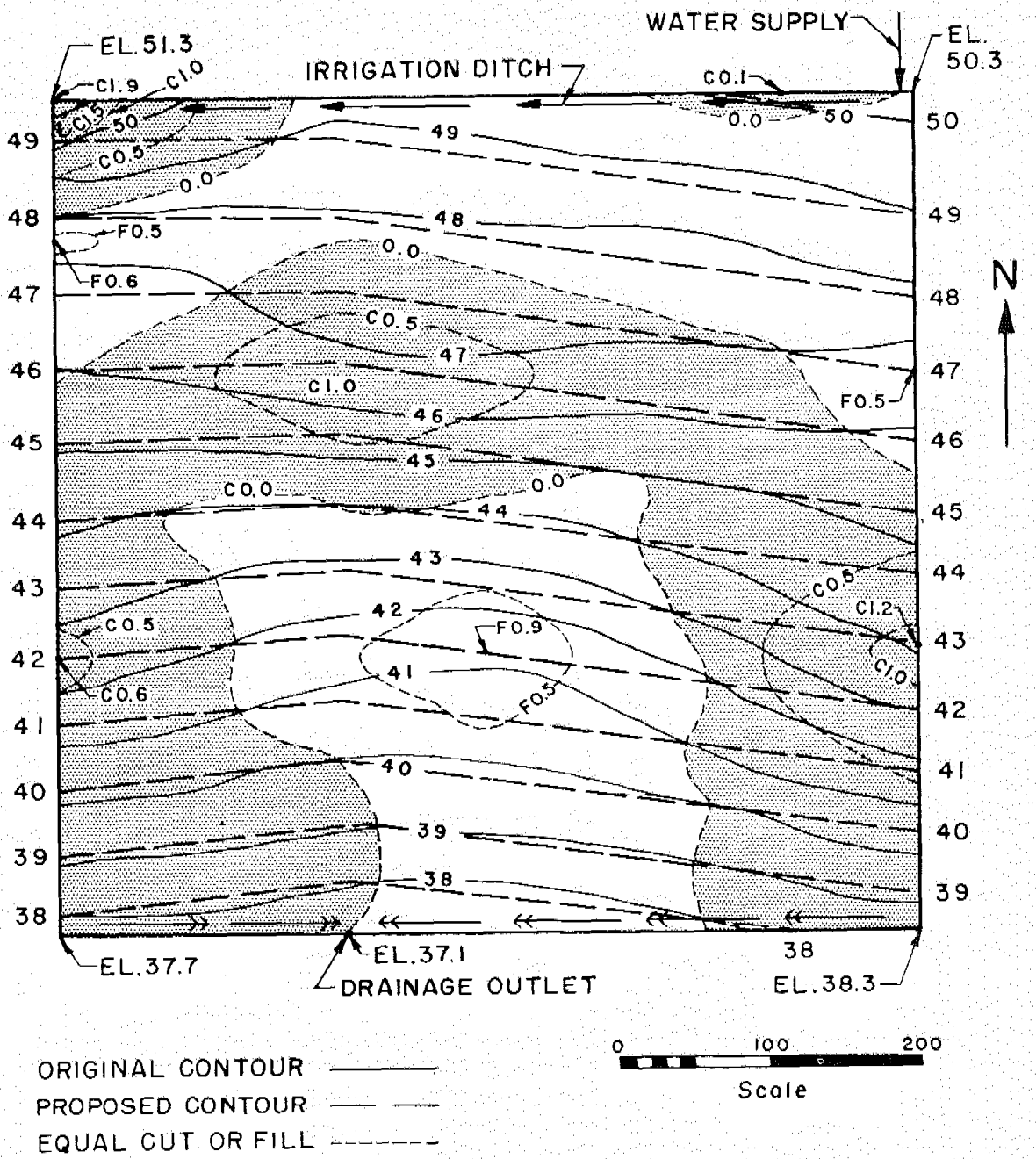


Figure 12-10.--The contour-adjustment method of land leveling.

Trial contours were then located. It was convenient to use an overlay on the original map for this purpose. In locating these trial contours, the area between the proposed and actual contours that represented excavation was made slightly greater than the area that represented fill. A sufficient number of contours were drawn to keep them less than 100 feet apart. It should be noted that on the example shown in figure 12-10 the final contours are straight lines, but on many fields, the finished contours may be curves.

Lines of equal cut or equal fill were then drawn through the intersections of the proposed and actual contours. The volumes of earthwork were computed by the horizontal-plane method later described in the section on Earthwork Calculations.

As expected, the first trial did not meet the established criteria nor have the proper ratio between excavation and fill. On a new overlay corrections were made, moving the proposed contours to the north to obtain additional, or to the south to reduce, the excavation. Care was also taken to keep the spacing between the proposed contours uniform or increasing in one direction only.

After several trials, the plan as shown on figure 12-10 evolved. It meets the limitations established. The surface relief as developed is Class C_1.

Since this design was accomplished without the benefit of a grid survey, it was necessary to utilize horizontal control to stake the field. Measurements were made along the sides of the field, locating the position of the proposed contours as scaled from the map. The points of deflection of the contour lines were similarily located by measuring from the field boundaries. From these points, the proposed contour lines were staked at 100-foot intervals. Levels were then run at these points and the cut or fill computed.

If the leveling is to be accomplished in progressive stages, permanent markers can be established along field boundaries and the proposed contour lines can be easily re-established at any time.

Some engineers prefer to use the contour-adjustment method even when a grid survey is available. Here, the procedure for obtaining the proposed finished surface is identical with that described but the elevation at each grid point is determined by interpolation between contours. The cut and fill at each grid point is determined by comparison between the original and proposed elevations, and earthwork volumes are computed by any convenient method.

When lands are steep and the surface is to be smoothed for irrigation by the contour-ditch or contour-furrow methods, the use of a grid survey and the contour-adjustment method is convenient. Irregularities in the contours can be smoothed on the map and the proposed elevations of the grid points determined by interpolation between contours. The summation method of computing earthwork volumes is commonly used since higher precision is seldom warranted.

Earthwork Calculations

Earthwork Volumes.
The exact method of computing the volume of earthwork in land leveling makes use of the prismoidal formula

$$V = L/6\ (A_1 + 4\ A_m + A_2)$$

Where

V = Volume in cubic feet.

L = Perpendicular distance between end planes in feet.

A_1 = Area of one end plane in square feet.

A_2 = Area of other end plane in square feet.

A_m = Area in middle section parallel to end planes in square feet.

The use of this formula is laborious, and approximate methods are commonly used.

The four-point method.—The four-point method is based on the formula

$$V_c = \frac{L^2}{108}\left(\frac{H_c^2}{H_c + H_f}\right) \quad \text{and}$$

$$V_f = \frac{L^2}{108}\left(\frac{H_f^2}{H_c + H_f}\right)$$

Where V_c = Volume of cut in cubic yards.

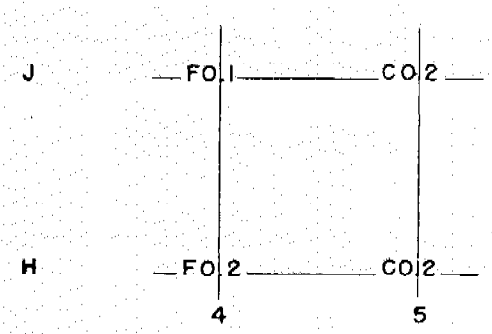
V_f = Volume of fill in cubic yards.

L = Grid spacing in feet.

H_c = Sum of cuts on four corners of a grid square in feet.

H_f = Sum of fills on four corners of a grid square in feet.

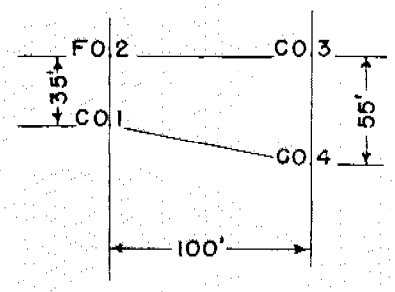
Using the formula, the volume of cut and fill in each grid square can be ascertained and the totals for the field obtained. Table 12-3 provides a rapid method for determining the excavation and fill in a 100-foot grid square. Let us examine the following grid:



The sum of the cuts are 0.4 and the sum of the fills are 0.3 Since the square is 100 feet to a side, the volume of earthwork as given by table 12-3 is

Excavation	21.2 cubic yards
Fill	11.9 cubic yards

The following methods have been found satisfactory for computing the volumes in other than square grids. For grids with four corners as



$$\text{Area grid} = \frac{35 + 55}{2} \times 100 = 4{,}500 \text{ square feet.}$$

Area in 100 x 100 grid = 10,000 square feet.

From table 12-3 for a 100 x 100 grid,

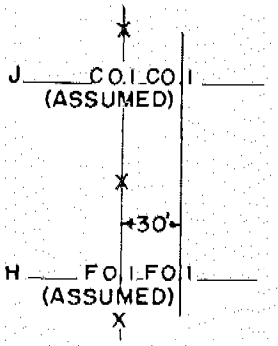
Cut = 59.3 cubic yards and fill = 3.7 cubic yards.

For the reduced grid

$$\text{Excavation} = 59.3 \times \frac{4{,}500}{10{,}000} = 26.7 \text{ cubic yards.}$$

$$\text{Fill} = 3.7 \times \frac{4{,}500}{10{,}000} = 1.7 \text{ cubic yards}$$

Correct use of the four-point method requires that the cut or fill be known at the outside edges of the field. In practice, however, stakes are seldom placed in the fence lines and usually it is satisfactory to assume that the cut in the fence line is identical with that of the nearest stake. Where abnormal conditions exist, plus stakes should be used. For the grid (0+30-1) (H-J) on figure 12-5, the following calculation was made:



Area in grid = 30 x 100 = 3,000 square feet.

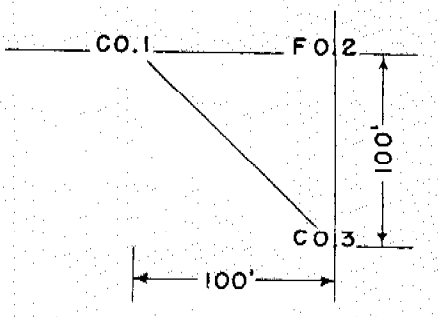
From table 12-3

C = 9.3 cubic yards.
F = 9.3 cubic yards.

Corrected = $\frac{3,000}{10,000}$ x 9.3 = 2.8 cubic yards

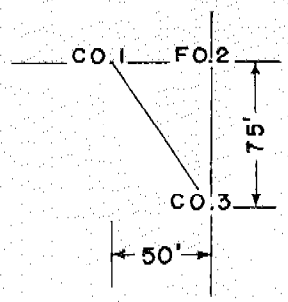
C = 2.8
F = 2.8

For a triangular area the sum of the three corners can be taken and the values in the table reduced to two-thirds. Thus,



Sum of cuts = 0.4
Sum of fills = 0.2
From table 12-3, C = 24.7 and F = 6.2
Excavation = 2/3 x 24.7 = 16.5 cubic yards
Fill = 2/3 x 6.2 = 4.1 cubic yards.

When triangular areas not 100 feet on each side are encountered, the volumes may be determined by further reducing the tabular values in proportion to the product of the length of the sides



Sum of cuts = 0.4
Sum of fills = 0.2

$$\text{Excavation} = \frac{50 \times 75}{100 \times 100} \times 2/3 \times 24.7 = 6.2 \text{ cubic yards}$$

$$\text{Fill} = \frac{50 \times 75}{100 \times 100} \times 2/3 \times 6/2 = 1.5 \text{ cubic yards}$$

The four-point method is rapid and gives an accuracy comparable to the accuracy of the original survey.

The end-area method.—The end-area method is based on the formula

$$V = \frac{L\ (A_1 + A_2)}{54}$$

Where

V = Volume of cut (or fill) in cubic yards.

L = Distance between end areas in feet.

A_1 = Area of cut (or fill) at one end in square feet.

A_2 = Area of cut (or fill) at other end in square feet.

The total areas (end area) of cut and of fill for each line in one direction, (i.e., A, B, C. D, etc., or 1, 2, 3, 4, etc.) are computed from the profile or taken directly from the plan. Thus, for the field shown in figure 12-5.

		Excavation			Fill		
Line	L	End area	Sum end area	Product	End area	Sum end area	Product
		Sq. Ft.	Sq. Ft.	Cu. Ft.	Sq. Ft.	Sq. Ft.	Cu. Ft.
N+25		288			84		
	25		576	14,400		168	4,200
N		288			84		
	100		458	45,800		207	20,700
N		170			123		
	100		411	41,100		258	25,800
L		241			135		
	100		322	32,200		352	35,200
K		81			217		
	100		132	13,200		396	39,600
J		51			179		
	100		136	13,600		370	37,000
H		85			191		
	100		223	22,300		231	23,100
G		138			40		
	100		267	26,700		112	11,200
F		129			72		
	100		288	28,800		140	14,000
E		159			68		
	100		427	42,700		68	6,800
D		268			0		
	100		557	55,700		0	0
C		289			0		
	100		356	35,600		57	5,700
B		67			57		
	100		67	6,700		227	22,700
A		0			170		
	50		0	0		340	17,000
A-50		0			170		
Total				378,800			263,000

$$\text{Excavation} = \frac{378,800}{54} = 7,015 \text{ cubic yards}$$

$$\text{Fill} = \frac{263,000}{54} = 4,870 \text{ cubic yards}$$

$$c/f = 1.49$$

The horizontal-plane method.—The horizontal-plane method is the end area method adapted to land areas instead of areas from cross sections. It is especially adapted for use when the contour-adjustment method of land leveling is utilized and on fields where there are heavy cuts and fills. It is based on the formula

$$V = \frac{H\,(A_1 + A_2)}{54}$$

Where

V = Volume of cut (or fill) between areas in cubic yards.

A_1 = Area of cut (or fill) C_1 in square feet.

A_2 = Area of cut (or fill) C_2 in square feet.

H = Difference between C_1 and C_2 in feet.

The accuracy of this method is best when values of H are small - i. e., 0.1 to 0.2 foot. H values as high as 0.5 foot are useful only for obtaining approximate quantities.

As shown on figure 12-10, lines of equal cut and equal fill were drawn on the map and the areas of each measured with a planimeter. Areas are expressed in square feet. The volume of excavation and fill on this field can then be computed as follows:

Cut or Fill Ft.	H Feet	Area Square Feet	Sum Area	Product	Volume Cu. Yards
			CUT		
0.0		189,100			
	0.5		220,000	110,000	2,037
.5		30,900			
	.5		33,000	16,500	306
1.0		2,100			
	.5		2,300	1,150	21
1.5		200			
	.4		200	80	2
1.9		0			
				Total	2,366
			FILL		
0.0		170,900			
	.5		180,400	90,200	1,670
.5		9,500			
	.4		9,500	3,800	70
.9		0			
				Total	1,740

Ratio cut to fill = 2,366/1,740 = 1.36

The summation method.--The summation method assumes that a given cut or fill on a stake represents an area midway to the next stake or on a 100-foot grid, 10,000 square feet. On this basis every foot of cut would involve a volume of

$$1/27\ (100 \times 100 \times 1.0) = 370 \text{ cubic yards}$$

This method is the least accurate of those shown. In those grid squares where cut changes to fill, the method gives values considerably greater than the true value. For that reason, it cannot be recommended for use except to obtain quick estimates of earthwork balance.

In using this method, the sum of all the cuts or fills in feet is determined and the total multiplied by 370 to obtain the yardage. If the "tenths" of cut or fill are added, the total is multiplied by 37.0. Points on the edge of a field are discounted in proportion to the area they represent. For example, the K line on figure 12-5 could be totaled as follows:

$$\Sigma C = 0.2 + 0.4 + 0.3 = 0.9$$

$$\Sigma F = (0.8 \times 0.1) + 0.1 + 0.8 + 0.2 + 0.1 + 0.1 + 0.2 + 0.2 + 0.2 + 0.2 + (0.8 \times 0.1) = 2.26$$

The volumes of earthwork represented by the area 50 feet on either side of this line are:

Cut = 0.90 x 370 = 33.3 cubic yards
Fill = 2.26 x 370 = 836.2 cubic yards

In the field shown on figure 12-9 the total cuts in the field added up to 19.4 feet and the fills to 13.3 feet. This would give a volume of

Cut = 19.4 x 370 = 7,178 cubic yards
Fill = 13.3 x 370 = 4,921 cubic yards

Comparison of methods.--To give an idea of the relative accuracy of these methods of computing earthwork, the field in figure 12-11 was computed by several methods with the following results:

Method	Cut	Fill	C/F
Prismoidal	6,732.8	4,474.7	1.50
Four Point	6,737.0	4,477.3	1.50
End Area	7,015	4,870	1.44
Summation	7,256	5,051	1.44

A comparison was also made for figure 12-10. To obtain cut and fill quantities to serve as a basis for the four-point and summation methods, grid points were established on 100-foot intervals. The original and proposed elevation of each grid point was assumed by interpolation between the contour lines. The following results were obtained:

Method	Cut	Fill	C/F
Four Point	2020	1252	1.61
Horizontal Plane	2366	1740	1.36
Summation	2490	1702	1.46

Earthwork Balance.

In land-leveling design it is essential that sufficient excavation be provided to construct the designed fills. When there is just enough excavation to do this and neither borrow nor waste is required, the earthwork is said to be in balance.

When a cubic yard of earth as measured in its original condition is loosened by excavation, its volume increases. This increase is known as "swell". When this same earth is placed in a fill and compacted, its volume decreases. The decrease as referred to the original volume is known as "shrinkage". Different soil materials have different properties in this regard. Some of the reasons which have been advanced by various engineers for the apparent high shrinkage factor required for land leveling are:

1. The bulk of materials moved in land leveling are top soils with a high organic content and relatively low original volume weight.
2. The cut areas in the field are subjected to considerable compaction by the earth-moving equipment. Hence the yield from an area of cut is less than that calculated.
3. In California Agricultural Experiment Station Circular 438, Mr. James C. Marr states: ". . . level ground surfaces between grade stakes appear to dip in the middle. To the extent that operators of the grading equipment allow this optical illusion to influence their judgment, crowning between grade stakes will occur".

Shrinkage of soil is variously expressed. For example, if one cubic yard of excavation of common earth will make 0.80 cubic yard of fill, it may be stated:

$$\frac{\text{Cut}}{\text{Fill}} \text{ Ratio} = C/F = 1.0/0.80 = 1.25$$

or

$$\text{Shrinkage factor} = \frac{1.0 - 0.80}{0.80} = 0.25 \text{ or } 25 \text{ percent}$$

or

$$\%\text{ Cut to }\%\text{ fill} = \frac{1.0}{1.8} \text{ to } \frac{0.8}{1.8} = 0.55 \text{ to } 0.45 = 55\% \text{ to } 45\%$$

Perhaps the most common approach in balancing earthwork is to vary the volumes of excavation and fill until the C/F ratio approaches a value believed to be valid for the conditions encountered. Experience in an area usually furnishes the background for selecting a value which proves satisfactory. Shrinkage factors usually vary from 10 percent for heavy leveling on firm field surfaces to as high as 100 percent for leveling with very shallow cuts and fills. Generally, the factor will be between 15 and 60 percent.

It is quite difficult to obtain more earth from an area which has been left a few hundredths high, but it is relatively simple to spread excess dirt and not exceed construction tolerances. For this reason, most equipment operators would prefer that the design shrinkage factor be somewhat high. On the other hand, the use of a high factor by the designer results in a higher computed yardage of excavation, and if the leveling is done on a unit-price basis, will result in a higher cost to the landowner.

When the plane method of leveling is used, it is convenient to assume that the whole field surface will be lowered by a certain amount by the compaction from the earth-moving equipment. This lowering can range from as little as 0.02 or 0.03 foot for very compact soils to as high as 0.10 foot for very loose soils. In the example in figure 12.5, lowering the plane 0.04 foot provided a C/F ratio of about 1.5. Lowering an additional hundredth would raise the C/F ratio to about 1.7 and raising it a hundredth would give a C/F ratio of about 1.3. With experience in an area, the amount that the plane needs to be lowered can be estimated as accurately as the C/F ratio required, and often, calculations to determine the earthwork volumes are omitted.

Construction

General.
Cut and fill stakes for construction purposes must be established to guide the equipment operator. When a grid-type survey exists, mark the cuts or fills directly on the original grid stakes. When the contour-adjustment method of design is used, set stakes as described in the description of the method and mark with the required cut or fill.

Equipment.
Most leveling is accomplished with tractor-drawn loading type scraper equipment. Tractors used are both crawler or rubber-tired wheel type and vary in size from small farm tractors to the largest heavy construction units. The variety of scrapers used is equally great since they must be chosen to match the power unit. Some of the points to consider in deciding how to do the job are as follows:

1. The time allowed to accomplish the work

Land leveling must fit somewhere into the cropping sequence, and often the number of days that a field is open for such work is limited. Where the period is long, small equipment may be used, but when time is pressing, it is wise to select large earth-moving equipment that can do the job in a hurry. It is important that the time to do the work is not underestimated.

2. The skill of the operator

If the equipment operator has not had experience in land-leveling work, it probably is advantageous to utilize small equipment. The slow rate of construction progress allows him more time to size up his work and make decisions. Land leveling is essentially a "finish grading" operation, and many operators with considerable experience in rough grading are not trained to work to the close tolerances necessary.

3. The haul distance

When the earth is to be moved over a considerable distance, the time in moving becomes an important segment of the cycle time. For long hauls, rubber-tired units usually will be best. When this equipment is used, it must have adequate power to load the scraper or be supplemented with pusher equipment.

On occasional jobs, the use of blade graders or auto patrols will be found useful. This is especially true for work in bench leveling where ridges are to be thrown up. They are sometimes used for leveling the benches themselves but if the benches are wide enough that tractor and scraper units can maneuver, the latter will usually be the most efficient.

Construction Procedure.
There are probably as many methods of approaching a land-leveling job as there are equipment operators and the following procedure is suggested as an example of how a job might be done:

A map similar to that shown in figure 12.11 is convenient for studying the best approach. The north side of the area might be considered as a logical starting point. To keep the haul distance to a minimum, it is important to construct the fills from the nearest excavation available. Excavation north of the M line could first be worked out by moving the dirt from the west edge of the cut area into the adjacent fill area until it was complete and then by moving the balance of the cut south into the fill area between the K-L and 7-14 lines. As the excavation between the M-N lines was complete, the L-M area of cut could be opened and the fills in the L-M lane completed. Work progresses to the south completing each lane of cut before moving out. The fill areas can also be progressively finished toward the south side. Since the earthwork balances, the last of the earth from the B-C-D lanes will be required to complete the fills in the A-B-C lanes.

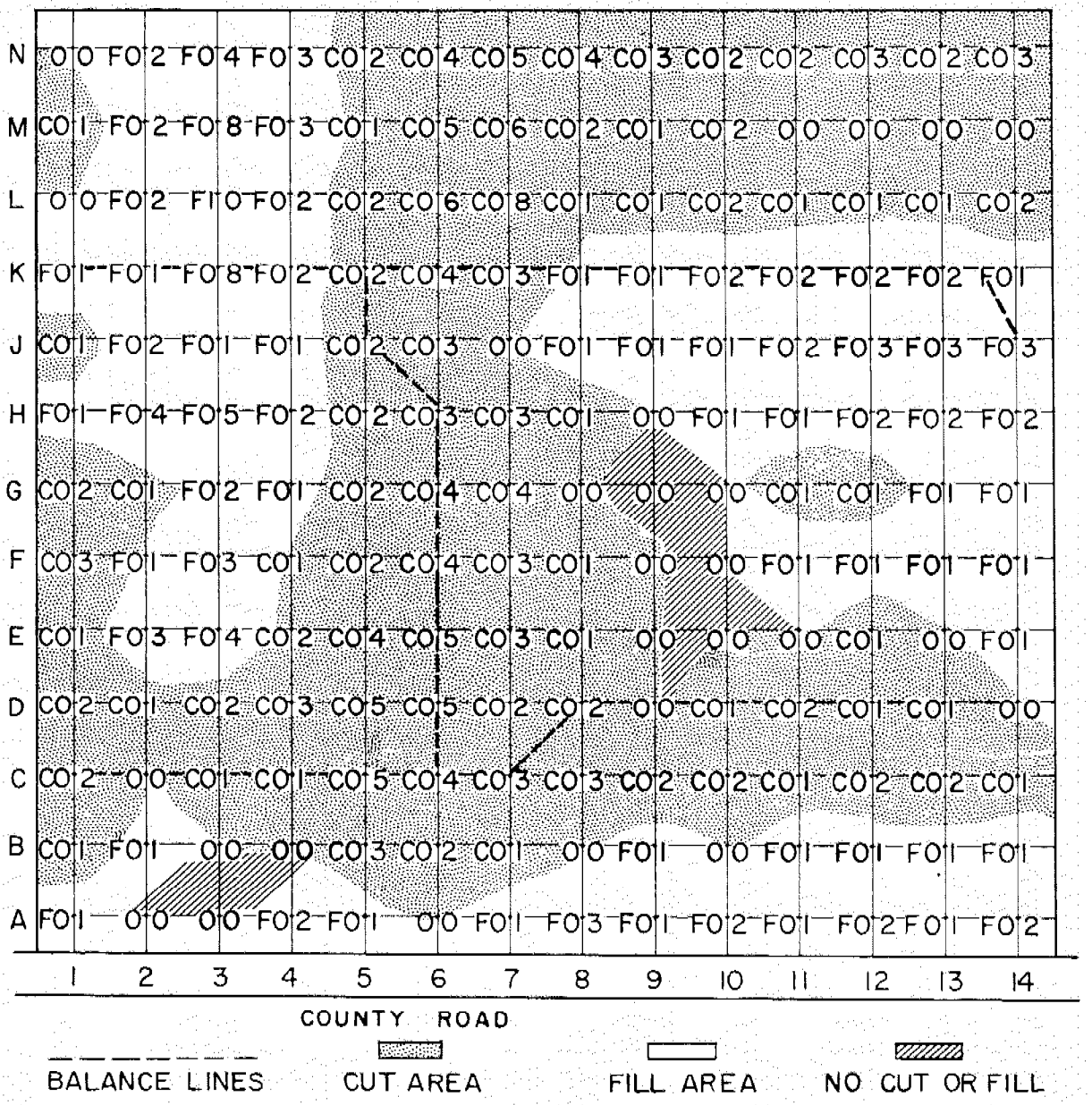


Figure 12-11.--Construction map for land leveling.

Some engineers prefer to make a detailed study of construction map and prepare balance areas in which there is just sufficient excavation to make the required fill. In figure 12-11, the field has been subdivided into four areas in which the earthwork balances. These can be further broken down into additional areas if one so desires. Each balance area is leveled as a unit insuring short-haul distances.

In performing these operations, do not disturb the grid stakes. In opening a lane, many operators prefer to first cut and fill a strip one scraper width wide adjacent to the stake line. After this is brought to the design elevation, work begins on the intermediate area. With this method it is easier to carry the grade by eye laterally across the lane. By working at a slight diagonal, the areas between stakes can be almost completely worked out until there remains only small "islands" around each grid stake. These are allowed to remain until the field has been checked.

When fills more than 0.5 foot are encountered, build them in layers not over 6 inches in depth to avoid excessive settling. In some areas it is common practice to provide extra fill height of approximately 10 percent to compensate for settlement.

When ridges are to be built as on the edges of contour benches, the volume of earth for the ridge should be available within a blade width of its finished location. Accomplish this by placing a small overfill on the edge of the bench. This extra fill should be one scraper width wide and one to three-tenths high depending upon the cross-sectional area of the dike. The blade can then crowd it into position. Another method is to leave a vertical bank between benches which is later sloped by throwing the dirt uphill and forming the dike.

Preservation of Topsoil.

Under some soil conditions it may be specified that the topsoil from an area must be stockpiled, the cuts overexcavated, and the topsoil replaced. The fill areas, too, must be stripped, the fills partly made with the materials available, and the topsoil replaced. Since this involves moving some earth twice, it is an expensive procedure and should be carefully justified.

When this operation is essential, first stockpile the topsoil from one lane on an area requiring little cut or fill. The cuts and fills in this lane should then be completed and the topsoil from the adjacent lane stripped and used for dressing the surface of the first lane. Then progressively across the field, move the topsoil to the adjacent lane as the leveling is completed until the last lane is dressed with the topsoil stockpiled from the first lane.

The "strip cut" method of land leveling is a modification which partially preserves the topsoil. This is described by M. E. Hoffman, United States Bureau of Reclamation of Minot, North Dakota.

> "The top six inches, or the plow depth, of soil normally contains most of the stubble residue, plant roots and humus materials. Difficulties in traction, loading and unloading operations are frequently encountered with this type of soil.
>
> These difficulties can be partially remedied by excavating alternate strips at double the designed cut depths thus facilitating capacity loading over shorter reaches.
>
> The 'strip excavated soils' consist of a mixture of topsoil and the more compact subsoil which can be unloaded more uniformly and leveled more readily.
>
> Leveling of the remaining alternate strips can be partially accomplished by routing empty scrapers over the edges of the cut banks. The balance of the leveling can be accomplished by diagonal operation of either a bulldozer or scrapers with the crowd gate in forward position."

Construction Tolerance.

Normally earthwork operations have a permissible tolerance of $\pm$ 0.1 foot. On flat slopes, however, it is usually necessary to make an additional restriction prohibiting reverse grades in the direction of irrigation. Normally it is impractical to accomplish a high finish with scraper equipment, and where possible the use of large land floats or planes are recommended to eliminate minor irregularities. The scraper work should be accomplished to the degree that two trips over with the float equipment will produce the desired finished surface.

Checking.

The final check must be made before the grid stakes are removed. On slopes exceeding 1 percent, it usually is adequate to check the cuts and fills at each stake with a hand level. On flatter slopes, use a level and ascertain elevations adjacent to each point. Grade between stakes must be uniform. Mark for correction the nonpermissible deviations from the prescribed grade.

When the field has been approved, the mounds and depressions left at the grid stakes are leveled to match the adjacent surface.

Finishing.
After the earth moving has been completed, it is advisable to plane the surface to remove minor irregularities. This is usually done by planing first at a 45-degree angle to the gridlines and again at right angles to the first operation.

Although a field may be leveled perfectly, sometimes after irrigation water is applied areas will settle unequally. Where deep furrow crops are grown, it may be advisable to irrigate by the furrow method for a year following leveling and delay the planing until after the initial settlement has taken place. Perennial crops should not be planted until settlement has taken place and corrections made.

Maintenance.
A leveled field requires maintenance to preserve its surface. Erosion from wind or water or improper use of farm plows and tillage equipment can seriously change its irrigating characteristics. Farm equipment such as two-way plows and tandem disks will eliminate dead furrows and ridges and so should be used. Smoothing with small farm floats should be frequently done. This practice should be regarded as a cultural practice--not a releveling operation.

Special Practices

Contour-Bench Leveling.
Contour-bench leveling is a method of preparing land for irrigation. The field is divided into a series of strips on the approximate contour, and each strip is leveled as an independent area. Thus a series of steps is formed down the slope. It provides a method of reducing grade on a field where excessive slope makes irrigation difficult or hazardous.

The advantages of contour-bench leveling are:

1. Irrigation water is easily controlled on the flat slopes, efficient irrigation methods can be used, and water-application efficiencies can be high.
2. Erosion from rainfall can be controlled. This permits soil-building processes that result in increased fertility and improved soil structure.
3. Since large stream sizes can be used and lengths of run can be comparatively long, labor in irrigating is lowered.
4. The flat slopes permit a more efficient use of both irrigation water and rainfall thereby reducing the quantity of irrigation water needed to meet plant requirements.

Disadvantages are:

1. Because the escarpment area between benches is too steep to farm, some area is lost to the production of the field crop. These areas can be seeded to perennial crops.
2. When the vertical drop between benches is over 18 inches, rodent control may be necessary to prevent washouts between benches.
3. The escarpment areas between benches present problems in maintenance and best utilization.
4. Waste irrigation water and runoff from rain accumulates high on the slope and must be conveyed to the lower edge of the farm.

Bench cross sections.—Selecting the proper cross section for contour benches is one of the most important phases of the planning. Figure 12.12 gives the shape normally used.

Determine first dimension W, the width of the farmable area. This width should be such that it will fit the farm equipment to be used. The least flexibility in farming is normally present with row crops and the width, W, should be in multiples of the width of the widest equipment anticipated. Unless farm roads are to be established at both ends of the benches, the width should be sufficient to allow round trips so that at the end of a tillage operation, the equipment is in position to move to an adjacent bench. The engineer should consider both the present and possible future farm equipment to be used in determining farmable width.

The relationship between W, T, and H may be expressed

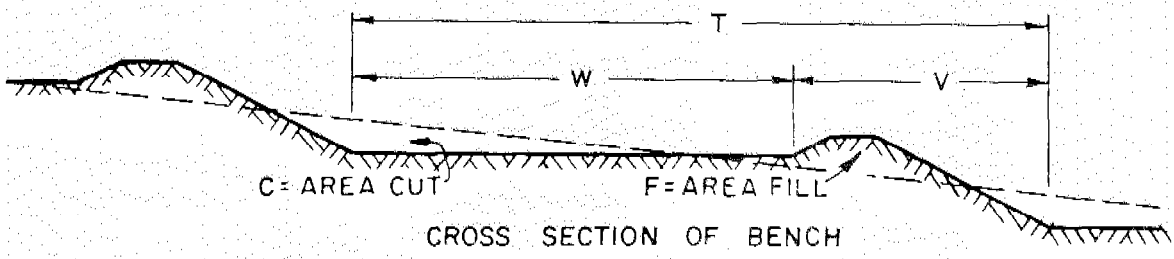
$$T = (W + B + 2hZ)\left(1 + \frac{SZ}{1 - SZ}\right)$$

and

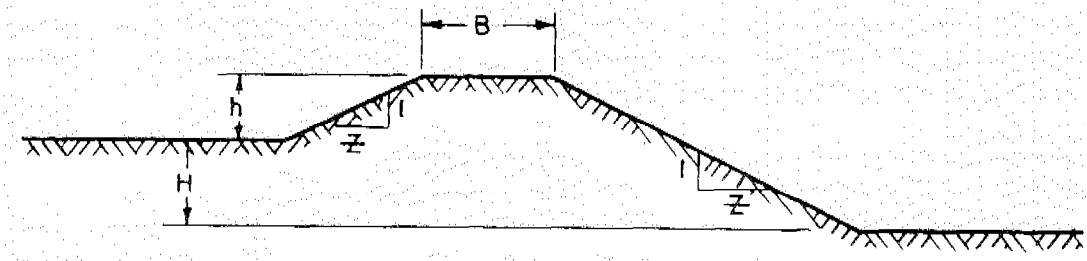
$$H = sT$$

where

T = Overall bench width in feet.
W = Width of farmable strip in feet.
B = Top width of dike in feet.
h = Height of dike in feet.
H = Vertical interval between benches in feet.
Z = Side slope of dike.
s = Slope of land in feet per foot.



CROSS SECTION OF BENCH



CROSS SECTION OF DIKE

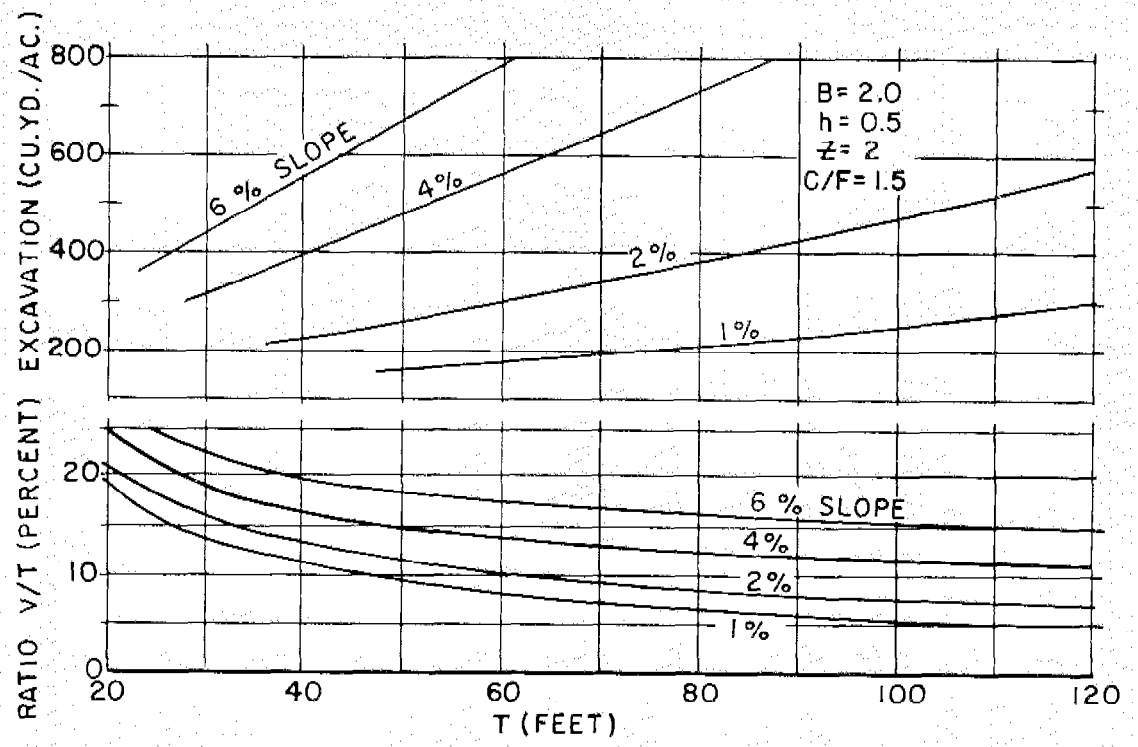


Figure 12-12.--Contour-bench relationships.

Another important consideration in selecting the bench spacing, T, is the area of land that will be utilized for the dike and escarpment areas. Depending upon crop and climate, this area may be nonproductive or of limited use. The relationship between the bench spacing, T, and the ratio V/T is shown on figure 12-12 for a typical dike cross section. Note that as the spacing, T, increases, the ratio V/T or the percent of land removed from production becomes less. Also note that as T increases, the volume of excavation required increases. The designer must select a spacing, T, which is a compromise between these two relationships.

The vertical interval between adjacent benches, H, must also be considered. On a given slope, as T or W increases, H also increases. As this dimension increases more than 1 foot, problems in maintaining the escarpment area increase rapidly. In only rare instances should H exceed 2 feet.

The height of the dike. h, should be sufficient to safely contain both the normal irrigation stream and storm runoff. Compute the depth of flows and provide a minimum freeboard of 0.2 foot above the maximum stage. On sandy soils or for pasture areas, increase the freeboard to 0.5 foot.

The side slopes, Z, should be selected with an eye to stability. 2 to 1 or 3 to 1 slopes are usual, but when stones are present in a field, the stones are often moved to the escarpment area and support a steeper slope.

The top width of the dike should be sufficient to prevent lowering of its height by trampling or by farm machinery. Usually the dimension B should be about equal to H, the drop between benches.

Bench location.—The location of the contour benches may be regarded as a part of the basic farm planning in which the field boundaries, irrigation water-supply system, drains, and field roads are located. For leveling, each bench is regarded as a separate field.

Since the earthwork involved is oftentimes great, lay out the benches to conform as closely to the original topography as farming operations and other considerations will permit. To make this layout, an accurate topographic map of the area under consideration is essential. It is necessary that this map have permanent points of reference for horizontal control located in the field since the benches will later need to be marked out using horizontal methods.

The need for a topographic map is lessened on flat, smooth slopes, and sometimes the bench location can be determined by inspection. It should be recognized, however, that the cost of a good topographic map is usually less than the cost of moving 15 cubic yards of earth per acre, and savings in earth volumes greatly in excess of this amount often result from intelligent use of a good map.

First separate the area to be developed into key areas, each having fairly uniform topographic features. In the field shown in figure 12-13, one key area might be considered to be the area between the 91 and 95 contours. Another is between the 88 and 90 contours.

Location of guidelines.—Guidelines should then be located which represent an average condition of each key area. This can be done by locating a line that represents the average shape of the contour lines and then computing the location of the guideline to the grade desired by offsets from the line representing the average of the contours.

In figure 12-13 random lines a, b, c, d, e, f, g, and h were drawn and the distance from a reference line to each contour within a key area was measured. The north fence line was arbitrarily picked to be the reference line. These measurements scaled as follows:

	Random line							
Contour	a	b	c	d	e	f	g	h
95	215	180	100	40	13	10	20	63
94	270	250	180	85	53	65	90	145
93	345	315	245	173	117	120	143	195
92	413	378	320	260	205	183	185	242
91	472	450	403	345	300	265	260	280
Average	343	315	250	181	138	129	140	185
90				425	390	355	330	330
89				495	463	433	413	413
88				635	550	505	475	475
Average				518	468	431	406	406

The average of the scaled distances as shown above represent the distance from the reference line to the average of the contours, and these latter lines can be plotted on the map.

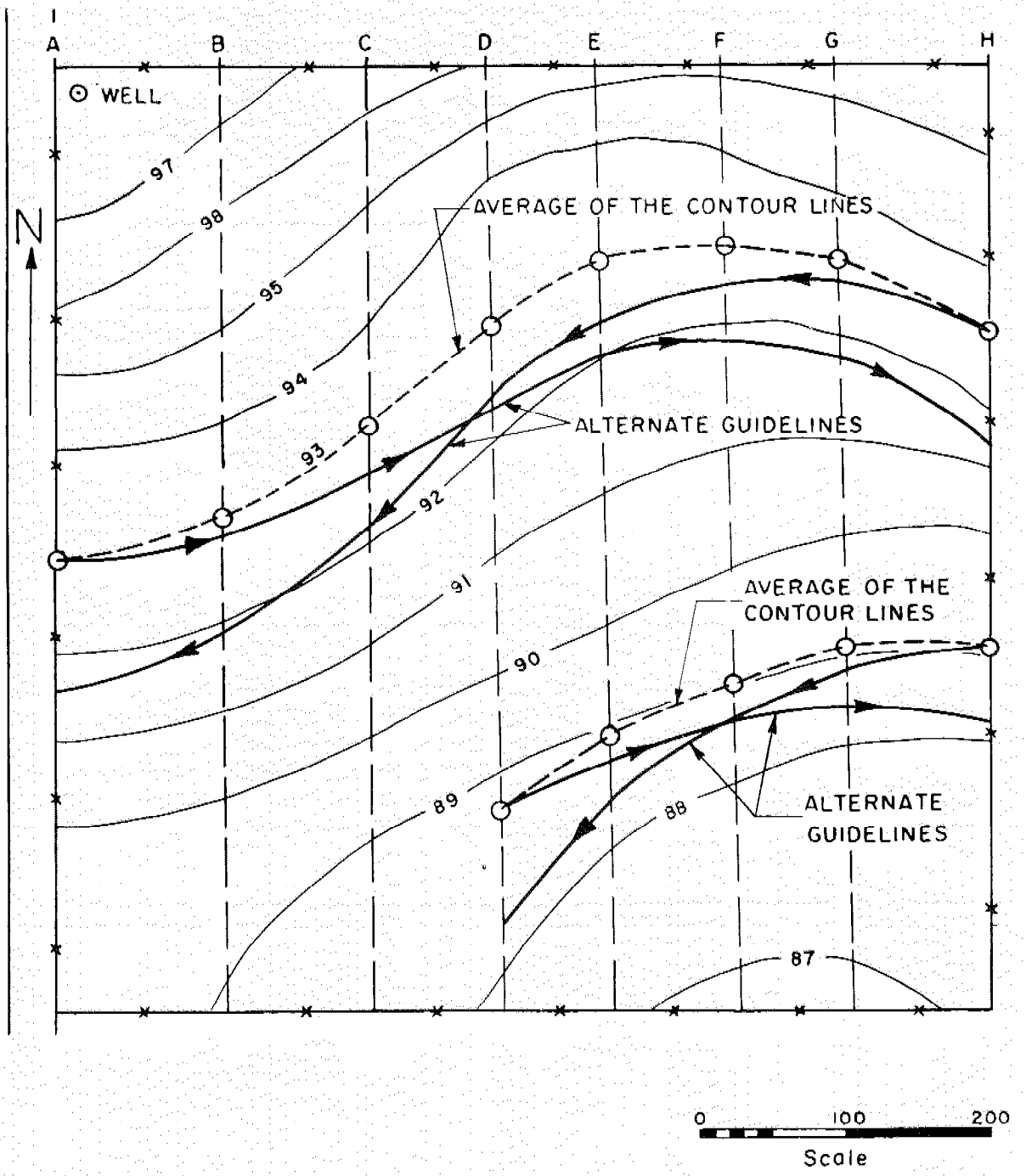


Figure 12-13.--Establishing guidelines for contour-bench leveling from contour map.

The average slope along the random lines in each key area should then be computed. Usually it is sufficiently accurate to determine this slope from the bottom edge to the top edge of the key area. The average slope is calculated by dividing the difference in elevation by the difference in distances from the reference line. For the field in figure 12-13 this becomes

	Random line							
Contour	a	b	c	d	e	f	g	h
95	215	180	100	40	13	10	20	63
91	472	450	403	345	300	265	260	280
Percent slope	1.56	1.48	1.32	1.31	1.39	1.57	1.67	1.84
90				425	390	355	330	330
88				635	550	505	475	475
Percent slope				0.95	1.25	1.33	1.38	1.38

Knowing the location of the line representing the average of the contours and the slope of the land, it is possible to determine the horizontal adjustment necessary to represent a guideline for any desired grade. For the problem in figure 12-13 it was desired that the benches should have a slope of 0.002. The following computations were made to determine the necessary horizontal adjustments assuming a grade first in one direction and then in the other.

Between contours 91 and 95								
Random line	a	b	c	d	e	f	g	h
Avg. slope percent	1.56	1.48	1.32	1.31	1.39	1.57	1.67	1.84
Station	0+00	1+20	2+30	3+30	4+20	5+00	5+80	6+95
Fall	0	0.24	0.46	0.66	0.84	1.00	1.16	1.39
Adjustment	0	16'	35'	50'	60'	64'	69'	76'
Station	7+30	6+10	4+80	3+70	2+80	1+90	1+10	0
Fall	1.46	1.22	0.96	0.74	0.58	0.38	0.22	0
Adjustment	94'	82'	73'	56'	42'	28'	13'	0

Between contours 88 and 90								
Random line	a	b	c	d	e	f	g	h
Slope percent				0.95	1.25	1.33	1.38	1.38
Station				0+00	0+90	1+80	2+60	3+60
Fall				0	0.18	0.36	0.52	0.72
Adjustment				0	14'	27'	38'	52'
Station				3+80	2+70	1+80	1+00	0
Fall				0.76	0.54	0.36	0.20	0
Adjustment				80'	43'	27'	14'	0'

An example of this calculation can be shown for the guideline falling to the east on the upper key area. Station 0+00 was considered to be at the intersection of the average to the contour line and random line a. By scaling, it was estimated that the stationing at the point where the guideline would cross random line b would be 1+20. Since the grade in the bench is to be 0.002, station 1+20 would be 0.24 foot below the average to the contour line. On line b, the average slope is 1.48 percent and the necessary adjustment (or the distance from the average to the contour line and the guideline) is

$$\frac{0.24 \times 100}{1.48} = 16 \text{ feet}$$

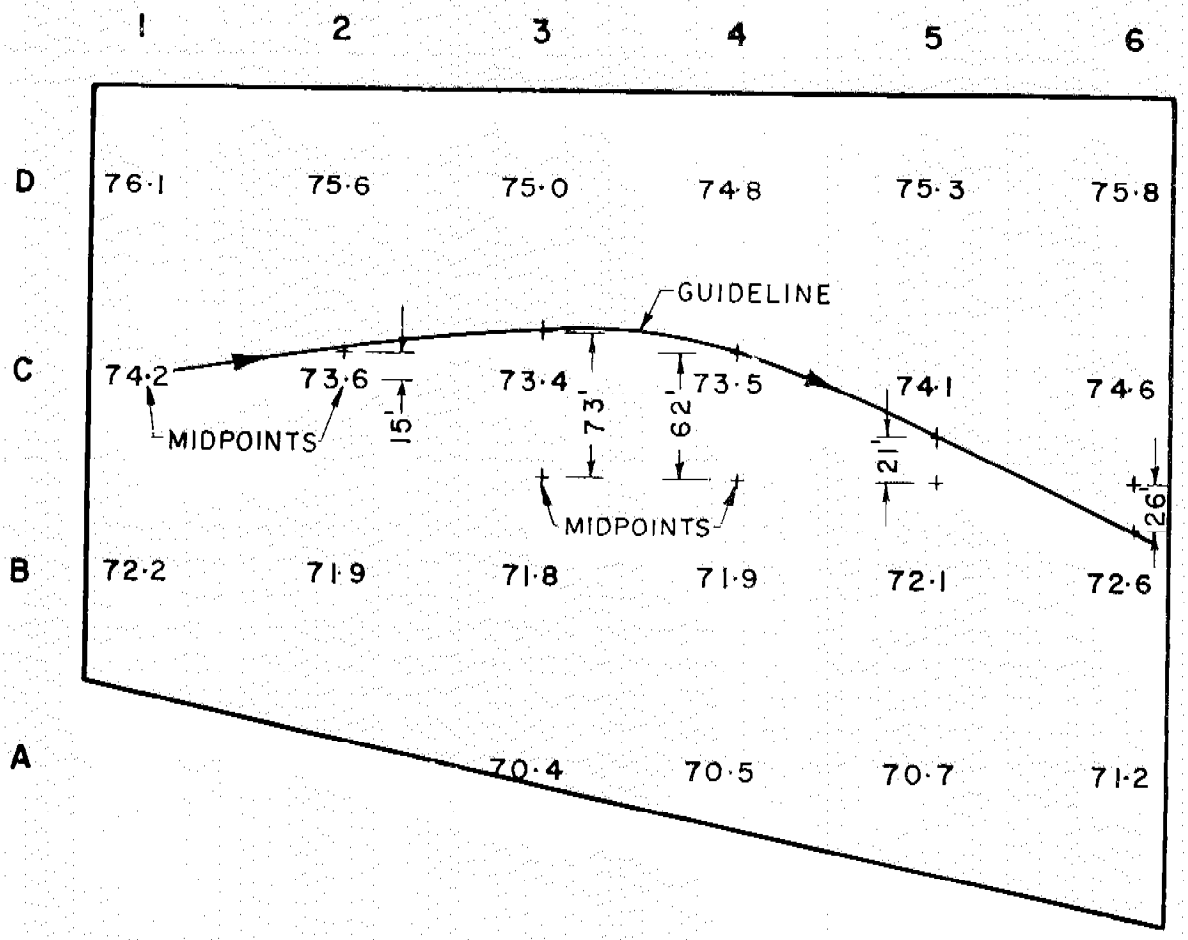
A point was then located 16 feet south of the average to the contour line and the stationing at that point checked against the original estimate. Since it was very nearly station 1+20, no further refinement was necessary. Similarly, points were found on random line b, c, d, etc. and the guidelines plotted.

Guidelines can also be located from a grid-type survey. This can best be described through the use of an example, figure 12-14. The elevations of each grid line approximately normal to the contour lines are first added and an average elevation for each line determined. Thus, on line 3, the sum of the elevations is

$$75.0 + 73.4 + 71.8 + 70.4 = 290.6$$

The average elevation is

$$\frac{290.6}{4} = 72.65$$



SUM OF ELEVATIONS	222.5	221.1	290.6	290.7	292.1	294.2
AVERAGE ELEVATION	74.17	73.70	72.65	72.68	73.03	73.55
PERCENT GRADE	1.95	1.85	1.53	1.43	1.50	1.53
STATION GUIDELINE	0+00	1+00	2+05	3+05	4+08	5+10
ELEVATION	74.17	73.97	73.76	73.56	73.35	73.15
ADJUSTMENT	0	+15	+73	+62	+21	−26

Figure 12-14.--Establishing guidelines for contour-bench leveling from grid map.

The average grade on each gridline is also determined. This usually can be done by subtracting the elevation on the lower edge of the field from the elevation on the upper edge and dividing by the distance (in stations) that the points are separated. For line 3, this becomes

$$\text{Percent grade} = \frac{75.0 - 70.4}{3} = 1.53 \text{ percent}$$

The average elevations are considered to lie on the midpoint of each grid line. Hence, on lines 1 and 2, the midpoint is on line C; but for lines 3, 4, 5, and 6, the midpoint is at B+50.

Calculations are then made to determine the adjustment from these midpoints. Starting at the midpoint on line 1 with an average elevation of 74.17 and assuming the grade of the guideline is 0.002, it is estimated that the point on line 2 will be approximately at station 1+00, and the desired elevation on line 2 is about 0.2 foot lower or 73.97. Since the average elevation of line 2 is 73.70, the desired point lies above the midpoint a vertical distance of

$$73.97 - 73.70 = 0.27 \text{ foot}$$

Since the slope is 1.85 percent, the adjustment to be made is

$$\frac{0.27 \times 100}{1.85} = +15$$

A point 15 feet above the midpoint was located, and the distance from the midpoint on line 1 was scaled. Since it is very nearly the estimated 100 feet, the point is satisfactorily located.

A similar calculation is made on line 3, then line 4, and progressively the horizontal position of the guideline is plotted.

Planning benches.--With the guidelines located, the engineer can then plan the bench location on the map as shown in figure 12-15. The closer the guidelines are followed, the less will be the earthwork required but compromises need to be made to eliminate point rows and conditions which will make farming difficult. In planning benches, the following points should be noted:

1. Avoid sharp bends. Normally tillage difficulties will be experienced if a deflection in alinement is over 45° sharper deflections can usually be broken into two segments.

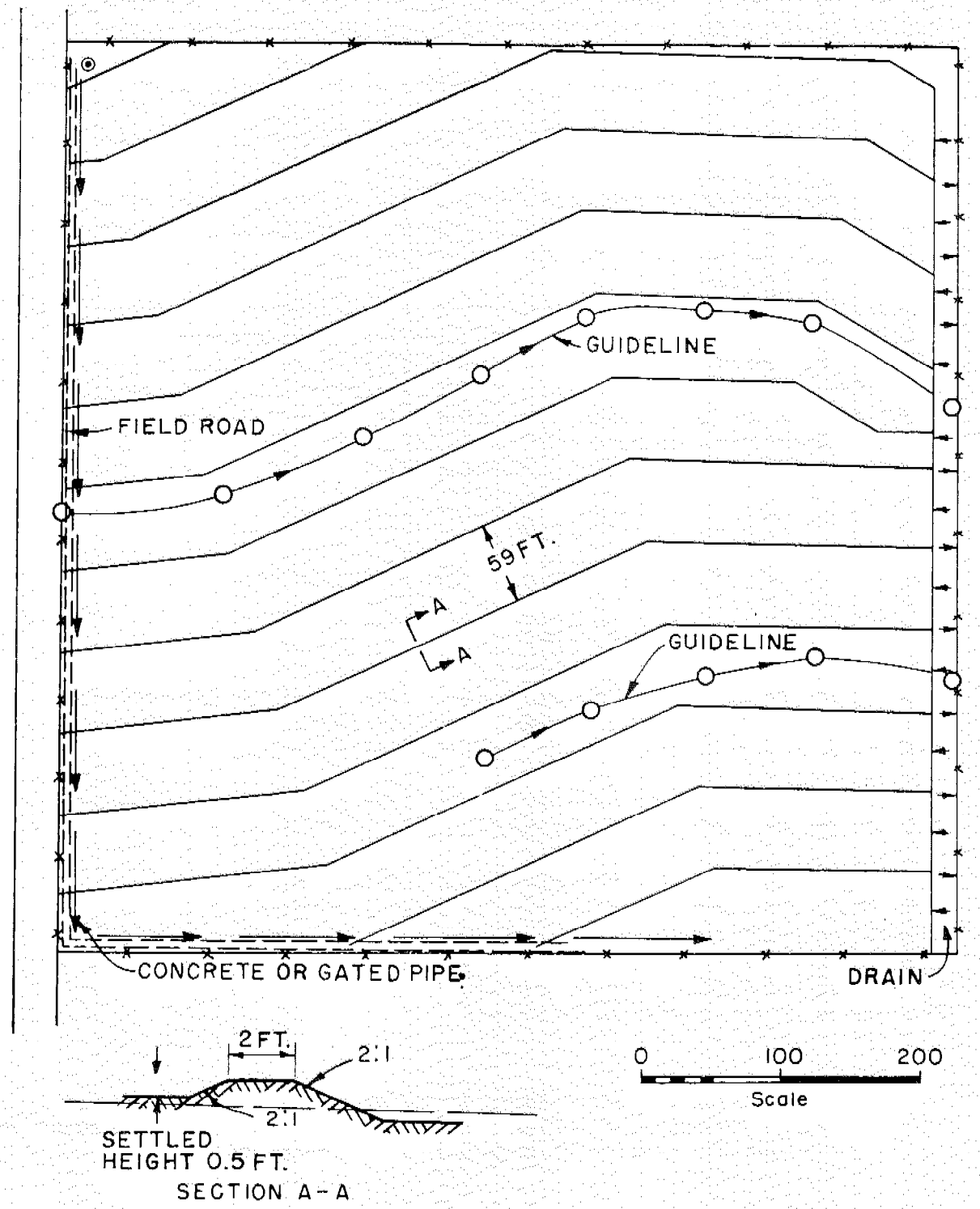


Figure 12-15.--Contour-bench leveling layout.

2. Normally benches should continue completely across the field. When it is necessary to terminate a bench in the middle of the area, remember to provide for an increase in the width of the dike and escarpment area for the adjacent benches beyond that point. An example of this is shown in figure 12-16 where this dimension was increased from 6 feet to 8 feet to take care of the increased vertical interval

3. Avoid pointed areas that are difficult to construct and maintain. Where one dike intersects another, make the angle of intersection about 90° in the manner shown on figure 12-14.

4. The bench spacing, T, should be changed whenever the average downfield slope at the location of the bench varies more than (1/2) percent from the slope used to calculate T. This insures the width of the bench, W, will be within 1+ foot from the intended dimension.

Staking.—The bench layout as planned on the contour or grid map must be transferred to the field. Usually one or two bench boundary lines are selected as controls and these are located on the ground by horizontal measurements from the points of reference for horizontal control established when the map was made. If a grid survey was used for planning, the bench boundaries may be established by measurement from existing grid stakes.

In figure 12-17 the lines F and J were selected. Line J was located in the field by first locating the ends of the east and west sides of the field. On the west, point (J) (0) was located 100 feet north of the fence corner. Point (J) (6+30) was located 20 feet west and 236 feet north of the southeast fence corner. One point of intersection was located by measuring 175 feet from point (J) (0) toward point (J) (6+30), turning a right angle and thence measuring 20 feet to the right. The other point of intersection was similarly located. All measurements were determined by scaling from the topog map.

Similarly, line F was located and the ends of lines 1, 2, 3, etc., were located along the north and south fence lines. The balance of the stakes were set by line and measurement as shown. The distance between the stakes on the numbered lines was calculated by the formula

$$\text{Distance} = \frac{\text{bench spacing, T}}{\text{sine of angle}}$$

For example, on the 2 line, figure 12-17, the bench width, T, was 59.0 feet and the angle was 64° 30 feet. Therefore, the distance along the 2 line was

$$\text{Distance} = \frac{59.0}{\text{Sine } 64^\circ\ 30'} = \frac{59.0}{0.903} = 65.3 \text{ feet}$$

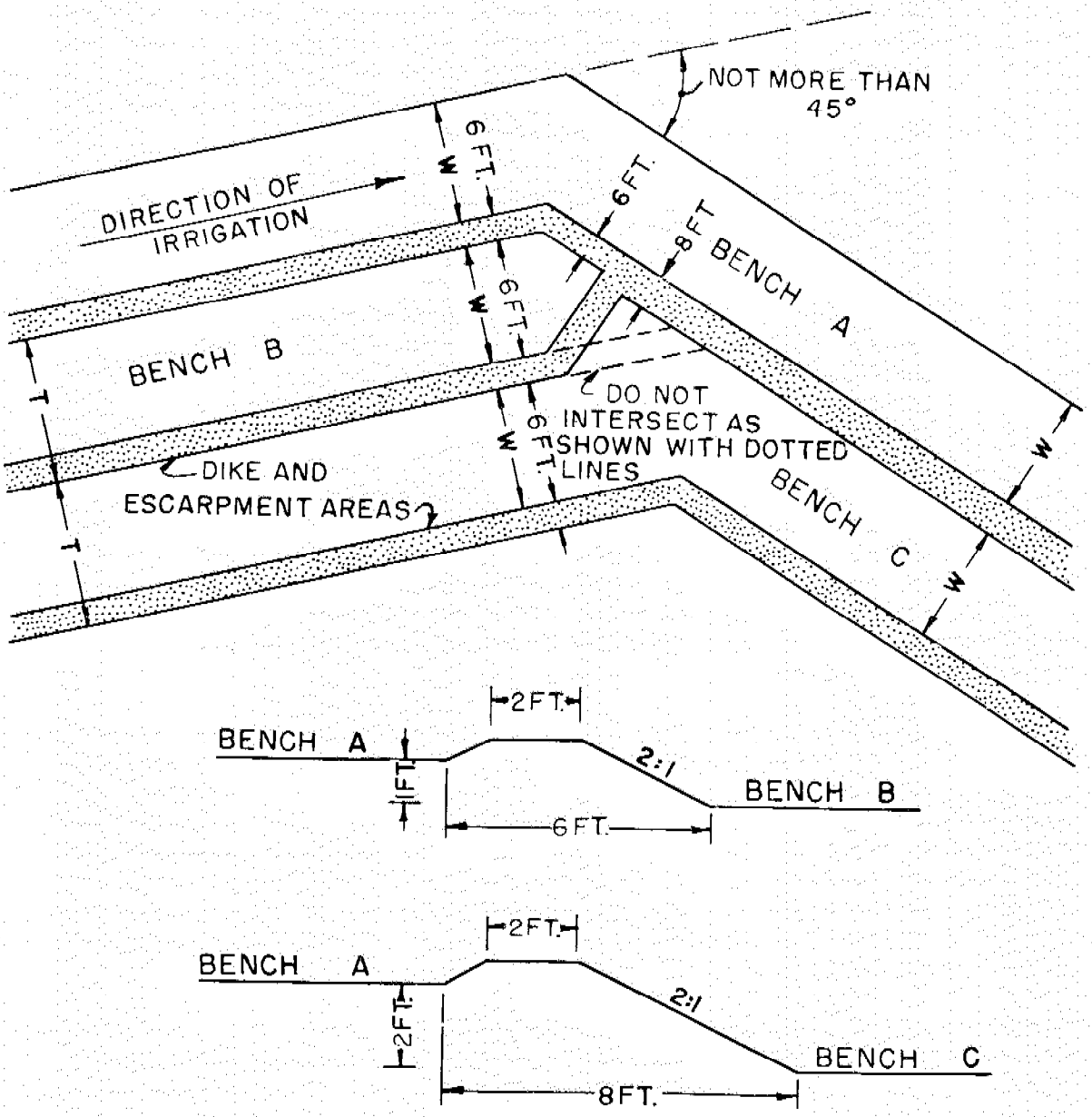


Figure 12-16.--Contour-bench details.

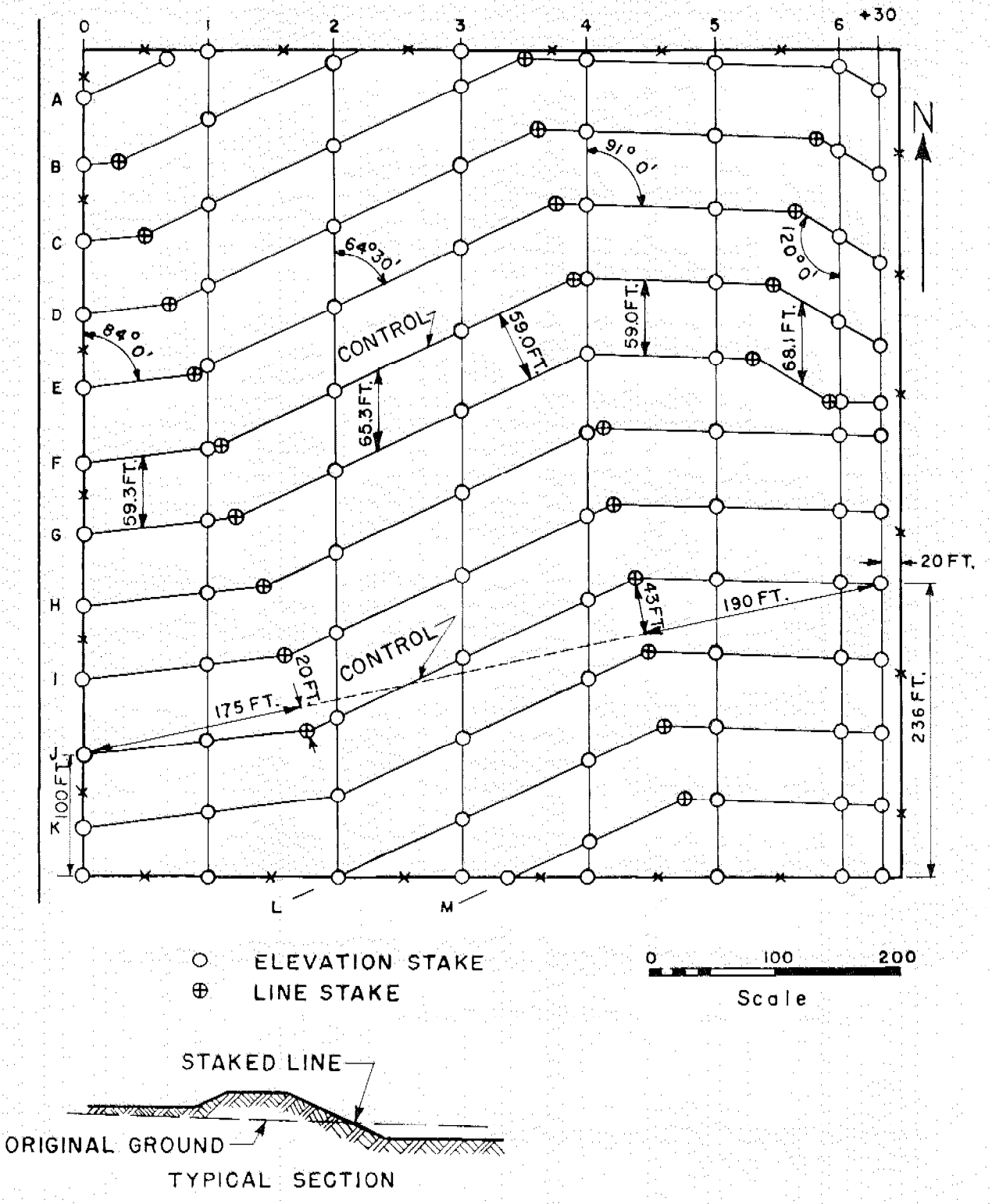


Figure 12-17.--Staking contour-benches--method 1.

After all stakes are set, elevation shots are taken for land-leveling design purposes. After the cuts and fills are computed, stakes are marked with a fill on one side for the area above and a cut on the other for the lower bench.

An alternate method of staking the field is shown in figure 12-18 The control lines are located as previously shown, and then the farmer uses row-marking equipment to carry parallel lines in both directions from the control lines to the adjacent bench boundaries. The farmer builds a small earth-marking ridge at each bench boundary using a border disk, single bottom plow, or similar equipment.

Stakes are then set on undisturbed ground on each side of the bench every hundred feet as measured along the centerline. For identification purposes, each bench is lettered, and the stakes are located by station and marked right or left, i.e., 3+00 L, or 3+00 R. No stake refers to more than one bench. While this method requires twice as many stakes as the one previously described, it is simpler, easier to stake, and each stake needs only one cut or fill marking. Difficulty may be experienced, however, in making accurate earth-volume calculations when this method is used.

Computing cuts and fills.--For purposes of leveling, each bench is regarded as a separate field. The plane method of land-leveling design is used with the single modification that the midpoint on the centerline is substituted for the centroid.

Figure 12-19 is an example of the calculations for one of the benches previously shown on figure 12-17. The average elevation of the bench was computed to be 90.46. The plane was then lowered 0.05 foot to provide the proper ratio between cut and fill.

The plane was further lowered sufficiently to provide earth for construction of the dike. This adjustment can be computed as follows:

$$\text{Cross-sectional area of dike} = \frac{\text{Top width x Base width x Height}}{2}$$

$$= \frac{2 \text{ feet} + 4 \text{ feet}}{2} \times 0.5 \text{ foot} = 1.5 \text{ square feet}$$

Assuming that it will require 50 percent more excavation to provide fill for the dike,

Cross-sectional area of excavation required - 1.5 x 1.5 square feet = 2.25 square feet

Bench spacing, T, = 59.0 feet

$$\text{Adjustment} = \frac{\text{Cross-sectional area required}}{\text{Bench spacing}} = \frac{2.25}{59.0} = 0.04 \text{ feet}$$

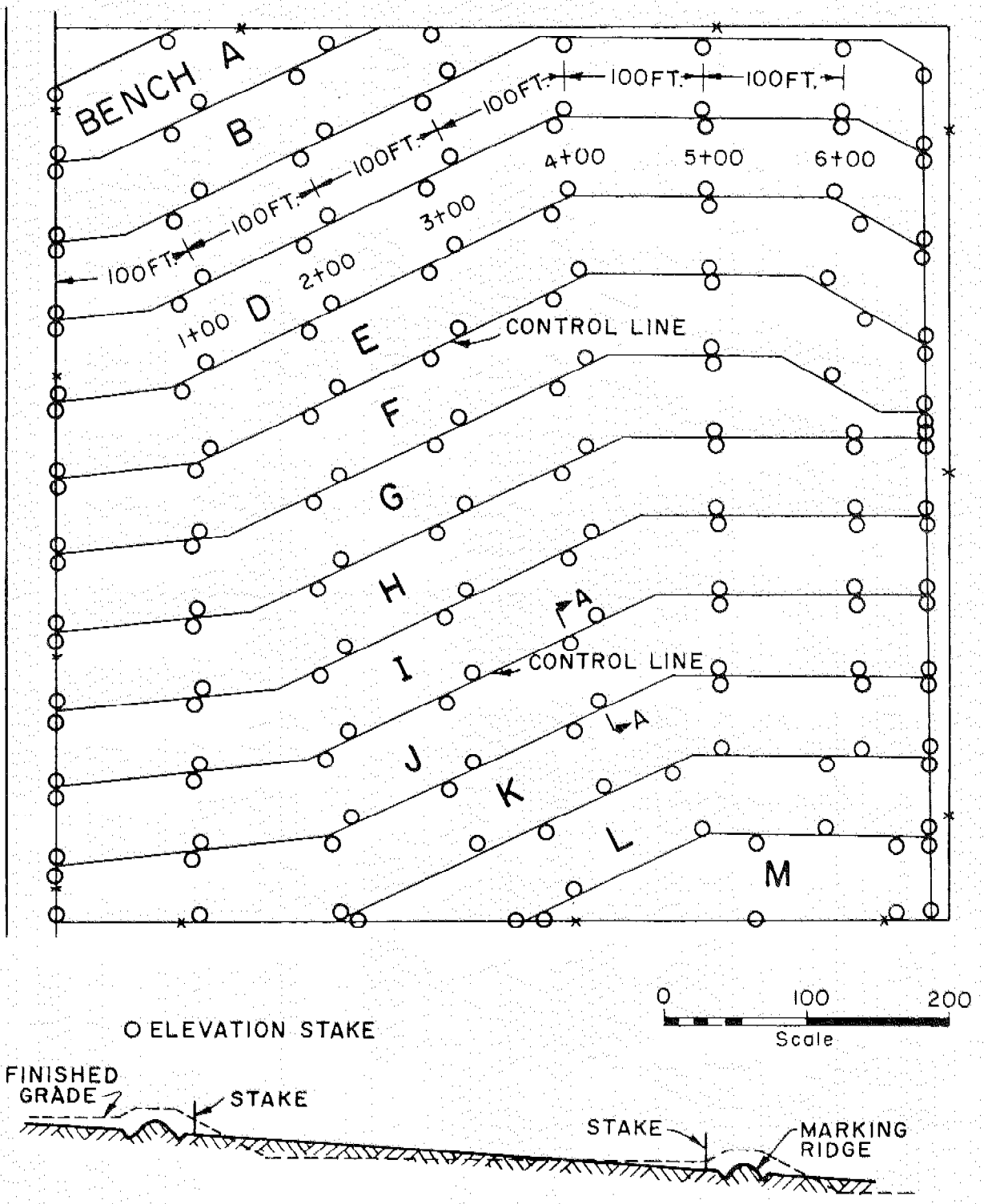
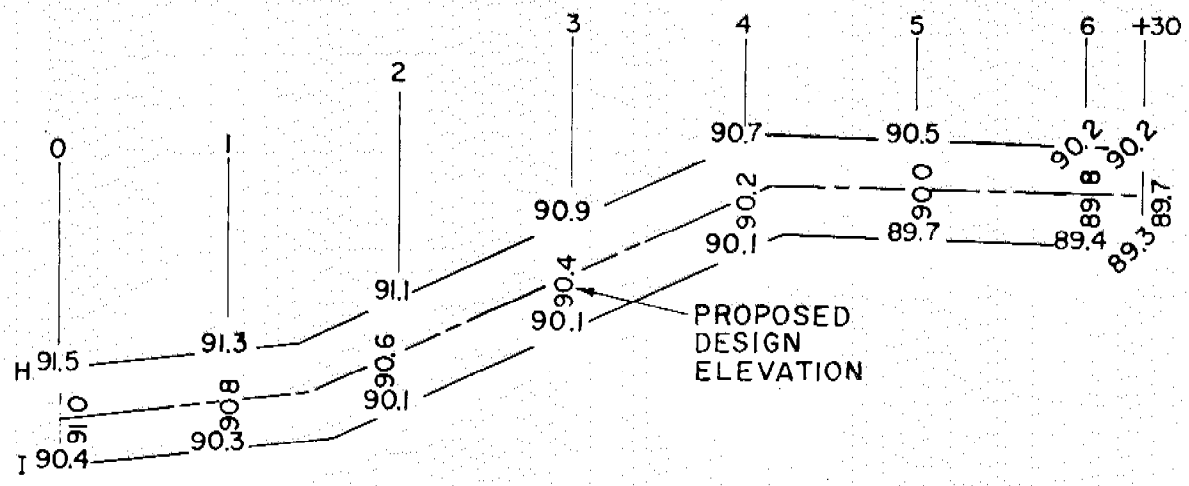


Figure 12-18.--Staking contour benches--method 2.



AVERAGE ELEVATION ON H LINE = $\frac{91.5+91.3+91.1+90.9+90.7+90.5+90.2}{7}$

LINE 0 TO 6 = = 90.89

AVERAGE ELEVATION ON I LINE = $\frac{90.4+90.3+90.1+90.1+90.1+89.7+89.4}{7}$

LINE 0 TO 6 = = 90.02

AVERAGE ELEVATION AT MIDPOINT = $\frac{1}{2}$(90.89 + 90.02) = 90.46

LESS ADJUSTMENT FOR SHRINKAGE	-0.05
LESS ADJUSTMENT FOR RIDGE	-0.04
DESIGN ELEVATION (LINE 3)	90.37 (90.4)

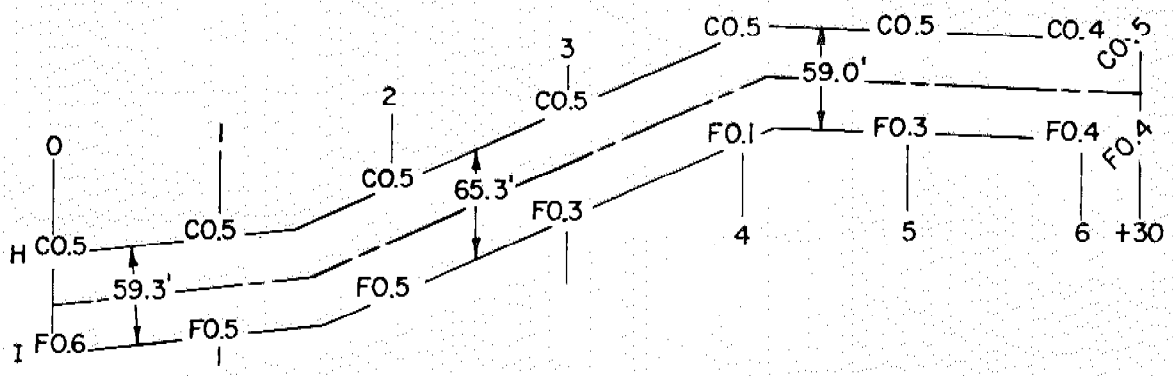


Figure 12-19.--Leveling calculations for contour benches.

The design elevation at the midpoint was computed and by applying the desired grade (0.002) from that point, the design elevations at all other points were calculated.

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