United States Department of Agriculture
Natural Resources Conservation Service

Part 623 Irrigation National Engineering Handbook

Chapter 7 Microirrigation

(210–VI–NEH, October 2013)

Issued October 2013

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Acknowledgments

Chapter 7, Trickle Irrigation, was originally prepared and printed in 1983 under the direction of Conservation Engineering Division (CED), Washington, DC, Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS).

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Chapter 7 Microirrigation

623.0700 Introduction

Experimental efforts in microirrigation (MI) date back to the 1860s. However, it was not until mid-1960s after the development and wide availability of low-cost plastic pipe and fittings that commercial MI became feasible.

During the last 40 years, many advances have taken place in the availability, quality, management, and performance of MI systems. Recently, the introduction of pressure compensated nonleak emitters and low-pressure and low-flow systems has further improved the performance of MI systems. These new developments have facilitated the use and diversity of use of MI in the United States and worldwide. In the United States, MI has increased from an estimated 500,000 acres (185,000 ha) in the 1980s to more than 2,500,000 acres (1,000,000 ha) in 2002. During this period, subsurface drip irrigation (SDI) has also been developed from a research tool to a widely used practice on diverse crops ranging from forage to orchard crops. It is estimated that in California alone approximately 250,000 acres (100,000 ha) of crops are irrigated by SDI systems.

Some advantages of MI include improved water and nutrient management, potential for yield increases, improved crop quality, and greater control of applied water. When adequately managed, MI will provide soil, water, and nutrient conservation; minimized leaching of soluble salts; and a reduced applied water requirement. These overall results have been shown to improve water use efficiency and economic returns.

This chapter of the National Engineering Handbook (NEH) describes design procedures for MI systems. It covers logical design procedures for the major types of MI 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 MI systems.

623.0701 Description

MI is defined as the frequent application of small quantities of water on or below the soil surface as drops, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line. MI encompasses a number of methods or concepts such as bubbler, drip, subsurface drip, mist or spray (USDA NRCS 2011). 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 and design of the emitter dissipates the operating pressure of the supply line, and a small volume of water is discharged at the emission point. Water flows from the emission points into the plant root zone through the soil by capillarity and gravity.

623.0702 Types of systems

(a) Drip irrigation

Drip irrigation (DI) is defined as a method of MI wherein water is applied at the soil surface as drops or small streams through emitters. Discharge rates are generally less than 2 gallons per hour (7.6 l/h) for single-outlet emitters and 3 gallons per hour per 3.3 feet (11.4 l/h/m) for line source emitters (ASAE Standard S526 2007). During the last 40 years, the interest and uses of DI have increased significantly as understanding of this irrigation/fertigation method improved. Plastic materials availability, manufacturing processes, emitter designs, and fertilizer improvement have also increased the use of DI. Specific installation equipment, components, and guidelines have further been developed, resulting in more consistent system installation and retrieval, improved performance, and longer life. The use of DI is increasing rapidly in areas where water conservation is important or water quality is poor and high economic yields are expected. Drip irrigation performs best when intensive and accurate management of water and nutrients are used. Figure 7–1 shows a blueberry field irrigated by drip hose suspended on wire. Figure 7–2 shows a grape vineyard irrigated by drip hose laid on the soil surface.

Figure 7–1 A pair of laterals with in-line drip emitter hanging on a wire in a blueberry field

(b) Subsurface drip irrigation

SDI is the application of water below the soil surface through emitters, with discharge rates generally in the same range as surface drip. This method of water application is different from and not to be confused with subirrigation where the root zone is irrigated by water table control (ASAE Standard S526 2007). The question often arises of how deep does the tape have to be buried to be considered SDI. Some researchers have even suggested that burial depths as little as 0.8 inch (2 cm) should be considered SDI (Camp 1998); but, the typical burial depth is between 4 to 24 inches (100–600 mm). During the last 20 years, use of SDI has increased significantly. Required design elements for SDI include strategically located vacuum relief valves and flushing manifolds. Specific installation equipment and guidelines have been developed, resulting in more

Figure 7–2 A grape vineyard irrigated by drip hose laid on the soil surface

consistent system installation, improved performance, and longer life. Subsurface drip irrigation performs best when the management recommendations employed include the use of high-frequency irrigation, accurate and continuous injection of required fertilizers, and real time automation. Figure 7–3 shows an excavated permanent SDI manifold used for field and vegetable crops.

Figure 7–3 Permanent SDI hose and manifold used for field and vegetable crops

(c) Bubbler

Bubbler irrigation is the application of water to flood the soil surface using a small stream or fountain. The discharge rates for point source bubbler emitters are greater than for drip or subsurface emitters, but generally less than 1 gallon per minute (3.785 l/min). A small basin is usually required to contain or control the water (ASAE 2007). Figure 7–4 shows a bubbler discharging water into a small basin. Similar manifolds can be used for tree and vine crops using different lateral spacings.

Figure 7–4 A bubbler discharging water into a small basin around the tree

(d) Jet, mist, and spray systems

Jet, mist, and spray irrigation are the application of water by a small spray or mist to the soil surface, where travel through the air becomes instrumental in the distribution of water (ASAE Standard S526 2007). These systems are also referred to as micro or mini-sprinklers. Jet, mist, and spray irrigation operate at low pressure and apply water at rates higher than drip, but typically less than 1 gallon per minute (3.785 L/h). Jet, mist, and spray irrigation systems wet a larger soil surface area than either drip emitters or tapes. Typically, jets have no moving parts and, thus, their radius of dispersing water is limited. Microsprinkler systems, like jets, operate at relatively low pressure, but include moving parts which enables them to discharge water over a larger area than jets. Figure 7–5 shows a microsprinkler irrigating an apple tree in an orchard. Figure 7–6 shows a small spray emitter with no moving parts.

Figure 7–5 A microsprinkler in an irrigated cherry orchard

Figure 7–6 A microspray emitter with no moving part

623.0703 Factors affecting the choice and type of a MI system

Several factors affect the selection of a MI system type. The grower must analyze economic parameters such as cost, anticipated profits, return on investment, and return on the water applied. Even before economics factors are analyzed, enterprise-specific constant physical factors such as climate, weather, soil types, soil characteristics, and topography should be evaluated. The grower should also prioritize limiting factors, operating expenses, and the potential long-term rate of return. The lists below identify some major factors and limitations that must be considered in these analyses; some are constant and some are variable.

Constant factors:

- climate and weather
- soil type and characteristics
- topography (slope)
- environmental quality

Variable factors:

- water prices and availability
- water quality/salinity
- pumping cost (energy)
- labor cost and availability
- system quality and cost
- operation and maintenance
- crop type and quality
- fertigation/chemigation
- education of the irrigator
- interest rates
- depreciation rate

Analysis of the constant factors will establish whether conversion should even be considered. However, because of the instability of the variable factors, a complicated analysis is needed, which requires professional advice and is beyond the scope of this chapter. As an example of the intricacies of the analysis within

a farming enterprise, consider the hypothetical effects of two factors on the probability of conversion to MI.

As the soil permeability increases, gravity irrigation becomes more difficult to perform, and the potential for deep percolation below the root zone increases. In areas where drainage and ground water contamination are problematic, growers should be encouraged to convert to microirrigation. Figure 7–7 shows the probability of MI systems being installed as soil permeability increases.

As the slope of the field increases, gravity irrigation becomes more difficult to perform, and the potential for deep percolation below the root zone and runoff increases. Figure 7–8 shows the effect of increasing field slope (%) on the probability of irrigation system conversion to microirrigation. There is also a high probability of conversion to microirrigation in areas where runoff, drainage, surface water, and ground water contamination are a problem.

623.0704 Advantages

MI offers many potential benefits in areas such as water conservation, plant response, farming operation, improved crop management, use of waste, saline and recycled water, adaptation to nontypical irrigation conditions, automation, minimum tillage, frost protection, distribution uniformity of water nutrients, and economics. Although these benefits are not exclusive to microirrigation as other irrigation systems can produce similar results, the combination of these benefits is unique to microirrigation.

(a) Water conservation

Based on published USDA-ARS lysimetric research conducted on several field crops in the California San Joaquin Valley, DI and SDI results averaged over several years have shown that slightly underirrigated crops can potentially conserve a significant amount of water, minimizing drainage, and do not decrease yields (Phene 1995).

Figure 7–7 Effect of soil permeability on probability of conversion to MI (adapted from Green et al. 1996)

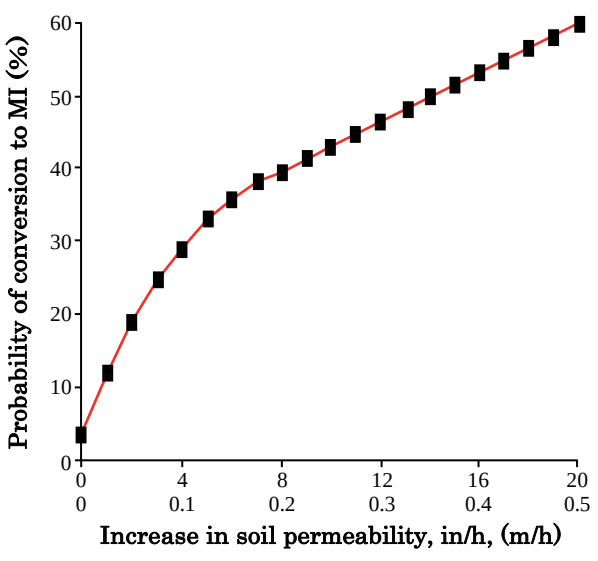
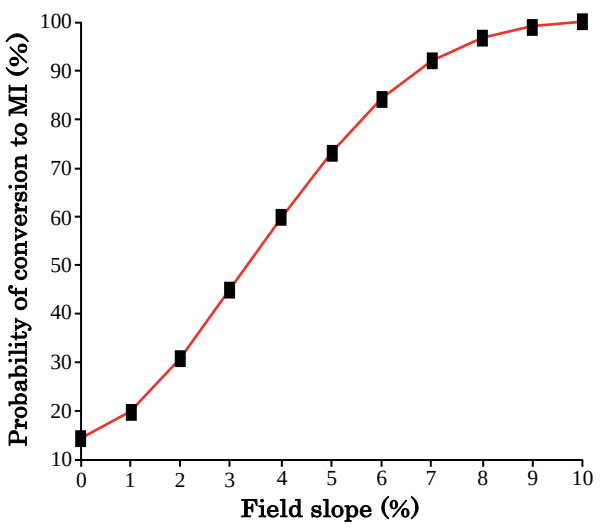


Figure 7–8 Effect of field slope on probability of conversion to MI (adapted from Green et al. 1996)



Depending on the scale of analyses, soil and water quality, design and management, and environmental conditions, MI may conserve water. How much water can be conserved will be site and environment specific.

(b) Farm operational cost savings

MI can reduce water losses and operating costs because the crop uses nearly all the water applied. Direct evaporative losses of water from plant and soil surface are limited to that portion of the soil surface wetted by the emitter. In the case of a well-designed and managed SDI system, the soil surface is maintained nearly dry at all times. Drip irrigation also minimizes weed growth and their nonbeneficial use of water, which in turn minimizes the use of herbicides and weed control tillage (fig. 7–9). When used with SDI, minimum tillage can be performed without disturbing drip irrigation laterals. Shallow rototilling of large crop residues and incorporation into the bed can be performed while retaining the bed integrity. Figure 7–10 is an aerial photo of a large, mature cotton field showing the difference in crop uniformity between the SDI-irrigated field (left hand side of photo) next to a furrow-irrigated field (middle and right-hand side of photo). The figure illustrates the uniform soil wetted pattern produced by a shallow buried DI system in a cotton field; note that much of the soil surface between the cotton rows is free of weeds and moisture. SDI offers another economic advantage: because water is applied below the soil surface, surface-induced infiltration variability is reduced, and the uniformity of water availability to the crop is improved.

Properly designed and managed MI systems do not produce irrigated-induced surface erosion, runoff, or deep percolation below the root zone. With MI, field shape and size become less of a consideration, and the whole available land area can be planted and irrigated.

(c) Improved crop management

Plant growth results from the metabolic process of photosynthesis, which is highly dependent on the water status of plants. MI potentially allows precision plant response to changes in crop water and nutrient requirements, environmental conditions, and even market timing. MI allows frequent application of small volumes of water and precise nutrient concentrations in the irrigation water in response to plant demand. In

Figure 7–9 Soil wetted pattern produced by a drip irrigation system in a cotton field *(courtesy C.J. Phene and Netafim, USA)*

Figure 7–10 Matured cotton field, showing the difference in crop uniformity between the SDI-irrigated field (left-hand side of photo) next to a furrow-irrigated field (middle and right-hand side of photo) (courtesy C.J. Phene USDA-ARS)

addition, MI systems will prevent crop-water stress by allowing continuous application of water even during cultivation and harvest.

With row and vegetable crops, the furrows under MI remain relatively dry, thus allowing workers and farm equipment field access. Fertilizers and approved pesticides can be injected in the water and distributed uniformly to the crop, thus avoiding exposure of workers and minimizing labor and farm equipment needed for their application. Greater control over fertilizer placement, pesticide treatment, and accurate timing of application through MI may improve crop performance and chemical application and loss. Crops grown under MI will typically have a smaller and denser root system that has access to a small, well-aerated, wetted soil volume. To achieve optimum response, crops must be maintained constantly at optimum water and nutrient status. To maximize potential benefits will require monitoring and automation similar to that used in greenhouses. Technology is commercially available for MI feedback, automation, and sensing that continuously respond to changes in environmental conditions and plant demands. However, systems and crops can be adequately managed without a fully automated system.

(d) Use of recycled and wastewater

In several States, agriculture wastewater, as well as secondary and tertiary treated domestic and industrial wastewaters (WW), are being used for irrigation of field crops, landscape, and ground water recharge and other applications. However, the use of treated WW for irrigation is subject to major concerns because of potential nitrate contamination of domestic water supplies.

The MI methods have been shown to successfully irrigate crops and minimize nitrogen nonpoint source agricultural pollution of surface and ground waters (Phene 1995). SDI systems in particular can improve safe handling of treated WW because the soil surface is not wetted and, thus, the potential for airborne contamination is negligible. In locations where year round cropping is possible, continuous disposal of WW can be carried out without the use of major storage facilities. However, storage facilities may be required during periods of low evapotranspiration or excessive precipitation. In areas where water is scarce and/or expensive, the use of WW for MI of landscape and crops can provide a viable alternative to conventional WW effluent disposal.

(e) Use of saline water

Crops have been irrigated with saline water since the beginning of irrigated agriculture. Under well-drained conditions, the soil salinity will approach the salinity of the irrigation water. The salt tolerance of a crop is usually appraised according to three criteria:

- ability of the crop to survive on saline soil
- yield of the crop on saline soil
- relative yield of the crop on a saline soil as compared to its yield on a nonsaline soil under similar growing conditions

The third criterion is usually the most used in the decision to irrigate with saline water and to estimate economic crop yield thresholds. Plants are adversely affected by the total water potential of the soil solution, which is mostly the sum of the matric and osmotic potentials (both are negative values with minimum being zero). The advent of MI has made possible the use of higher salinity water by using high-frequency irrigation to maintain a stable and higher soil moisture profile (matric potential close to zero), which compensate for the higher salts in the rootzone of the crops. The use of saline water for irrigation of crops allows higher quality water to be reserved for domestic uses.

(f) Use of MI in nontypical irrigation conditions

As shown in figure 7–8, the topography of a field is an important factor in the choice and motivation to implement a MI system. MI has rendered steep land manageable for agricultural purposes. More recently, the introduction of pressure compensated (PC) and nonleak pressure compensated (CNL) emitters has contributed greatly to the efficiency of drip irrigation design and its uses on rolling terrain and slopping land. The costly and energy intensive use of laser leveling required for flood and furrow irrigation can be avoided with PC and CNL drip irrigation systems. A detailed topographic survey should be performed to identify the topography and geometry of the field for design and installation purposes. Figure 7–11 shows a steeply slopping vineyard irrigated by a drip system

that could not be easily irrigated otherwise without generating significant runoff.

(g) Use for frost protection

Microsprinklers have been widely used for radiative and advective frost protection of citrus, apple trees, and vines. Mini and microsprinklers are selected to provide frost protection by using the heat released by the water cooling and changing state from liquid to solid (ice) and by increasing the soil thermal conductivity, which in turn allows an increase of the soil heat flux towards the soil surface. There are three methods of frost protection:

- undertree or canopy
- overhead
- targeted

An additional advantage of overhead frost protection systems is their ability to provide evaporative cooling for heat protection. The principle involves the heat of vaporization of water (heat absorbed by water to change it from a liquid state to a vapor state; heat of vaporization of water equals 540 cal/g). This process relieves the plant surface temperature rather than cooling the ambient air. Evaporative cooling of plants can improve fruit quality and may accelerate maturity by relieving water stress.

Figure 7–11 Grape vineyard on steeply slopping land irrigated by using pressure compensated emitters

(h) Potential improved distribution uniformity of water and chemicals

In general, with MI distribution, uniformity of water and chemicals is not affected by soil characteristics such as infiltration, salinity, crusting, permeability, and bulk density. Rather, product and system design, manufacturer's variation, installation, management, and age of system can introduce distribution problems in time and space. With nonpressure compensating-emitters, variation in surface elevation can introduce variation in the discharge rate due to change in pressure. Temperature variation due to an exposure and location along the lateral can also introduce variation in emitter discharge rates. One of the advantages of SDI systems is the minimum exposure of the drip lateral to temperature variations resulting in a more constant water temperature in the laterals.

623.0705 Disadvantages

The main disadvantages of MI systems are their comparatively high cost; proneness to clogging; tendency to build up local salinity; and, when they are improperly designed, installed, and managed, low distribution uniformity.

(a) Cost

MI systems are initially expensive to purchase and install, but they may pay for themselves within a short period of time if properly designed, installed, and managed. Their potential for increasing yield and conserving water often allow the user to recover its initial cost within 1 to 3 years, depending on the crop. For a mature orchard, the cost could be recovered in 2 to 3 years and perhaps 1 to 5 years for a new orchard, depending on the type of orchard. In general, MI systems are expensive because of their requirements for large quantities of piping and filtration equipment to clean and distribute the water. System costs can vary considerably depending on the type of system being installed, the crop, terrain, and quantity and quality of water available. Steep terrain may require the use of pressure compensated, nonleak emitters and several pressure regulators in the system. Because of different spacing requirement, some crops require fewer laterals than others. The degree of automation may also affect the cost; but, the convenience, safety, and labor saving may quickly pay for itself. Although costs are relatively high, under adequate design and management, these costs do not reduce profitability.

(b) Clogging

MI emitter outlets typically vary from small to very small, and they can become clogged easily by chemical precipitation of minerals, nonfiltered particulate or organic matter, root intrusion, and sometimes the combination of these things. Clogging can change emission discharge rates, decrease uniformity of water distribution, and eventually cause plant water and nutrient stresses. 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, lateral flushing, and proper filtration of water can usually prevent or correct the majority of emitter clogging.

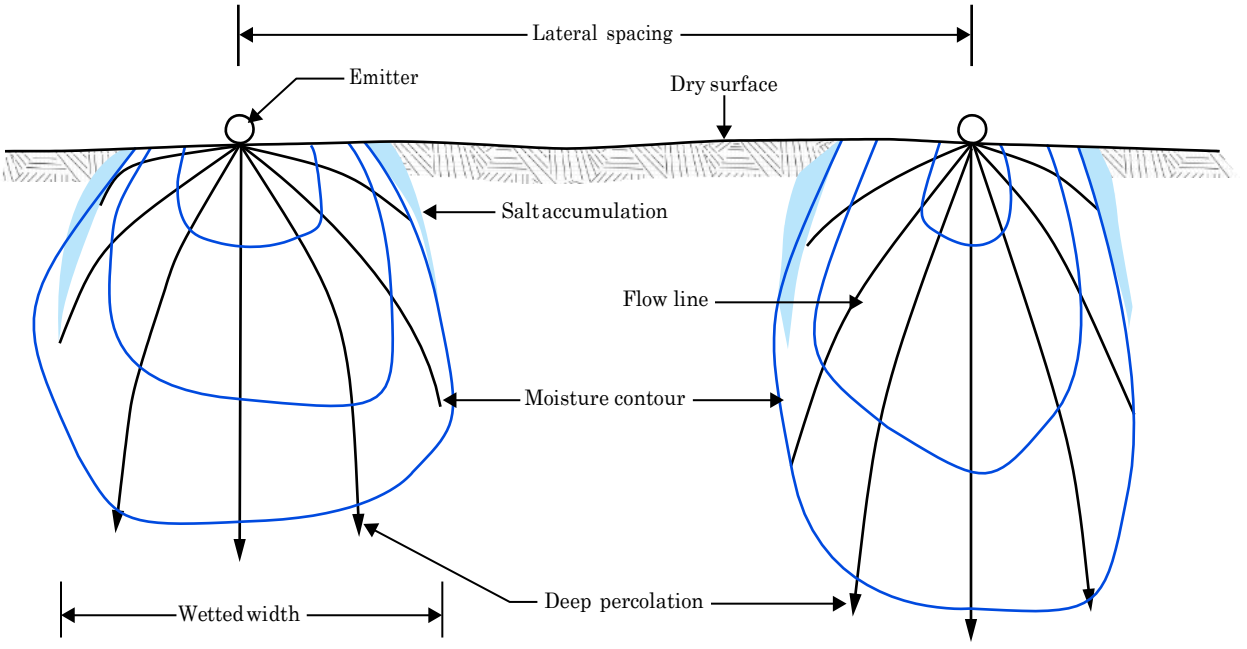
(c) Lack and/or decrease of uniformity

Most MI emitters operate at low pressures, 3 to 20 psi (0.21–1.41 kg/cm^2). In the past, if a field sloped steeply, the emitter discharge during irrigation could have differed by as much as 50 percent from the volume intended, and water in the lines may have drained through lower emitters after the water was shut off. Some plants received too much water; others received too little. The introduction of CNL emitters has mostly eliminated this problem. However, assuming that the manufacturer's coefficient of variation (the ratio of the standard deviation of the discharge of the emitters to the mean discharge of the emitters) is adequate (10% or less), factors other than manufacturing and design may affect the emitter uniformity in time and space. For instance, black polyethylene plastics exposed to sunlight will cause the discharge rate of exposed emitters to vary due to thermal expansion and high water temperatures. Water evaporating at the discharge orifice of the exposed emitter also increases salt concentration, precipitation and accumulation of salts, which in time may reduce the size of the orifice.

(d) 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. 7–12). When a rain of less than 2 inches (50.8 mm) falls after a period of salt accumulation, irrigation should continue on schedule to ensure that salts leach below the root zone. Depending on soil texture and amount of accumulated salt, rain in excess of 2 inches (50.8 mm) will usually be sufficient to dilute and leach salts. During drip irrigation, salts also concentrate below the surface at the perimeter of the soil volume wetted by each emitter (fig. 7–12). 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.

Figure 7–12 Typical soil moisture pattern under surface drip irrigation, showing salt accumulation at the surface of the soil volume wetted by each emitter



(e) Potential root intrusion

Root intrusion, which occurs mostly when plants are stressed and roots are seeking moisture and nutrients, is mostly a problem specific to SDI systems. Design of some emitters minimize the problem better than others, but usually the best way to prevent root intrusion is to seasonally inject herbicides in the water (trifluralin or Treflan® approved for injection for weed control) or lower the pH of the water by injecting acids. The use of high-frequency irrigation to maintain an anaerobic, saturated zone around the emitters can also help minimize root intrusion. Continuous injection of low concentration of phosphoric acid (15–25 ppm, mg/kg) will also minimize root intrusion.

(f) Root pinching with SDI in orchards

Root pinching of the drip laterals is mostly a problem encountered in SDI systems. It is a more prevalent problem with certain tree species, such as pistachio (fig. 7–13), which have a very large and aggressive root system. It is also a problem that can be minimized by installing the drip laterals as far from the trunk (optimally half way between the tree rows) and as deep as possible and installing the drip laterals at planting of a new orchard. Installing drip laterals in an existing orchard will cut roots close to the drip laterals and emitters. This usually causes roots to produce scar tissues and to grow back aggressively, often pinching off the laterals.

(g) High level of operation/maintenance

The management of MI systems, and drip and SDI in particular, is more intensive than that of conventional irrigation systems; however, much of it can be performed remotely via computer and with local weekly inspections so that the management cost is often decreased after the first or second year of operation.

Preventive maintenance of drip irrigation systems and SDI, in particular is critical to efficient operation and long life. It is especially critical after installation and during testing. All lines (mains, submains, laterals, or flushing manifolds) should be flushed until all foreign particles (soil and PVC shavings) are out of the system.

A good test to determine if flushing is no longer needed consists of taking a clean glass jar, filling it with flush water, and looking into the sunlight to ascertain that particulate matter is not floating or settling in the jar. Based on the distance from the system headworks, the acreage covered by the system, and the flushing velocity, this could take up to several hours. Following the initial flushing, the frequency of maintenance flushing during the season will depend greatly on the water quality, the filtration method and efficacy, and the chemical maintenance of the water.

Monitoring pH and electric conductivity (ECw) and using these data to determine required injection of acid to prevent chemical precipitation is usually necessary when the pH of the water is above seven and carbonates and bicarbonates are present in concentrations two to three times the sum of the calcium and magnesium ions. This is almost always the case in arid and semiarid climates where the soils are calcareous and rainfall is limited. In areas where the pH is on the acid side, or where iron and other biological activity can be a problem, water should be treated with chlorine. Chlorine injection is most effective at low pH and at the end of the irrigation cycle. Chlorine residual should be checked at the furthest flushing point from the headworks and the residual chlorine should be about 3 to 4 parts per million (ppm) (3–4 mg/L) 30 minutes after the end of the irrigation.

Figure 7–13 An example of a root pinching the SDI lateral (cut lateral on the right) in a pistachio orchard with the SDI lateral installed 5 feet (1.52 m) from the tree row and 18 to 20 inches (0.46–0.51 m) deep

(h) Rodents and insects

Rodents and insects are known to chew polyethylene laterals. Rodent damage can be prevented by rodent control or use of large diameter rigid wall materials for laterals. Some problems can be prevented by providing alternative water sources for coyotes, dogs, or other animals. Insect damage can be controlled by injection of pesticides. With SDI systems, insect problems are minimized, especially when the laterals are installed below 12 inches depth (0.3 m). Rodents (gophers, mice, moles) are not a major problem if the laterals are installed at 18 to 24 inches depth (0.45–0.60 m). Also ensure that the wetted area from each emitter overlap so that the entire lateral is in wetted soil. Gophers or rodents prefer digging in dry soil. Wall thickness of 35 to 55 mil is recommended for installation of SDI laterals at depths below 12 inches (0.3 m).

(i) System malfunctions

One filtration malfunction can result in the plugging of many emitters that then must be cleaned or replaced. Safety screen filters should always be installed downstream of the primary filters. A properly designed monitoring and control system will sense these incidents and quickly turn off the irrigation system, thus minimizing the emitter damages caused by these problems.

(j) Germination of field crops

SDI germination of field and vegetable crops can be achieved with or without alternate irrigation methods. Depending on the soil texture and the depth of the SDI ,lateral, sprinkler, or furrow irrigation can be used to germinate field and vegetable crops. However, with most medium- to fine-texture soils, moisture can be brought up to or near the soil surface by pulsing the SDI system. Using a sweep implement, a small V-shaped trench can be opened into the moist soil. The

seeds or transplants can then be planted in moist soil. As the seedlings emerge and grow, the soil can be used to bed up the crop.

(k) Disposal of used polyethylene tapes

Disposal of used polyethylene (PE) presents environmental concerns and impacts as well as additional costs. Mechanical equipment is now available to retrieve used PE tapes from the fields. Tapes are collected, cleaned up, and recycled by manufacturers. The recycled PE can be mixed with new PE or used on its own, depending on the products being manufactured.

623.0706 Water quality factors and considerations affecting the performance of microirrigation systems

Water quality and its chemistry are directly related to clogging of MI emitters. When the chemistry of irrigation water is not adequately considered, clogging can be one of the major problems affecting this method of irrigation. Clogging can be caused by physical, chemical, and biological contaminants or a combination of these. Before any solutions to clogging can be offered, the exact causes for the process must be determined (Bucks et al. 1979). Because there are so many variables involved in clogging of emitters, there are no foolproof quantitative methods for predicting the amount and rate of clogging (Gilbert and Ford 1986). However, by analyzing the water quality before designing and installing a MI system, the potential for clogging may be estimated, and problems may be minimized. Water quality factors can be divided into three major categories: physical clogging caused mostly by suspended solids, chemical clogging resulting from chemical precipitate, and biological clogging resulting from algae and bacterial populations.

Table 7–1 summarizes the physical, chemical, and biological factors that can potentially clog MI systems (adapted from Bucks and Nakayama 1980). Tentative water quality criteria were proposed by Bucks and Nakayama and are presented in table 7–2.

(a) Physical factors

Physical factors summarized in table 7–1, such as suspended inorganic particles, organic materials, and microbiological debris will cause clogging of MI systems. Suspended particles may be carried into the irrigation water supply from open-water canals or wells. These particles are often introduced into the supply lines during installation or repair. They must be flushed out from the supply system before laterals and emitters are connected to the supply line. Physical factors can be controlled with proper filtration and periodic flushing of laterals.

Table 7–1 Physical, chemical, and biological factors potentially clogging MI systems (adapted from Bucks and Nakayama 1980)

Physical factors (suspended solids)	Chemical factors (precipitates and others)	Biological factors (bacterial growth)
Inorganic particles	**Calcium and/or magnesium carbonates**	**Filaments**
Sand	Calcium sulfate	
Silt	Heavy metals	
Clay	Hydroxides	
Plastic	Carbonates	
Metal	Silicates	
	Sulfates	
Organic particles (Aquatic organisms)	**Oil and other lubricants**	**Slimes**
Zooplankton		
Snail		
Fish		
Organic particles (Nonaquatic organisms)	**Fertilizers**	**Microbial ochres**
Insect larva	Phosphate	Iron
Ant	Aqueous ammonia	Sulfur
Fish	Iron, copper, zinc	Manganese
Spider	Manganese	

Table 7–2 Tentative water quality criteria for classifying waters used with MI (adapted from Hanson et al. 1994; Hassan 1998)

Type of factor	Minor	Moderate	Severe
Physical			
Suspended solids[a]	50	50–100	>100
Chemical pH	7.0	7.0–8.0	>8.0
Dissolved solids[a]	500	500–2,000	>2000
Manganese[a]	0.1	0.1–1.5	>1.5
Total iron[a]	0.2	0.2–1.5	>1.5
Hydrogen sulfide[a]	0.2	0.2–2.0	>2.0
Carbonate+bicarbonate[a]	50.0	50–100	>100
Biological			
Bacterial population[b]	10,000	10,000–50,000	>50,000

a Maximum measured concentration from a representative number of water samples using standard analytical procedures for analysis in ppm (mg/L)

b Maximum number of bacteria per milliliters can be obtained from a portable field sampler using standard analytical procedures for analysis

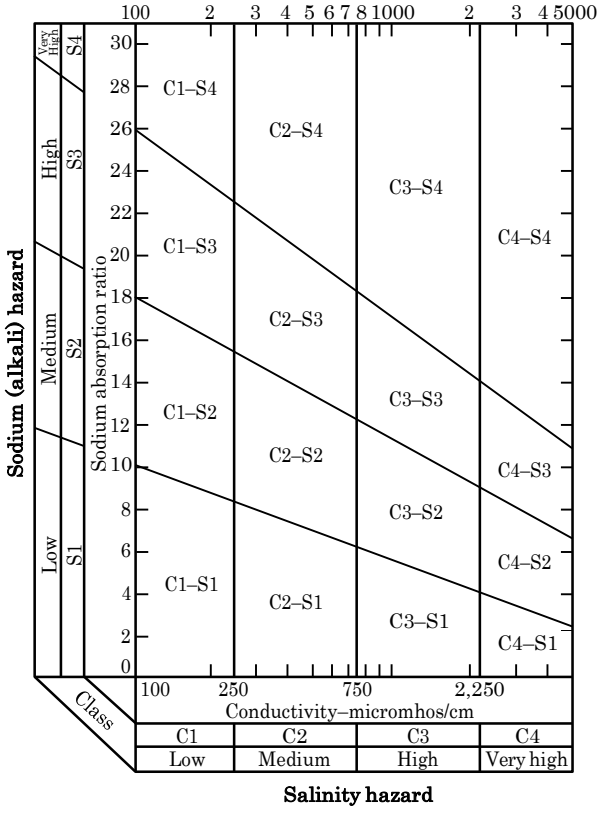
In addition to settling ponds, filtration, flushing, and choice of emitter orifice size, a good filtration system is always needed for microirrigation. The filtration system's design characteristics should consider water quality, velocity in the laterals, and the diameter of the emitter specific flow path. When no manufacturer's filtration recommendations are available, filter for one-tenth of the diameter of the emitter's smallest opening. Filtration will be addressed in NEH623.0708.

(b) Chemical factors

The important characteristics of irrigation water affecting its quality can be summarized as total concentration of soluble salts, the relative proportion of sodium to other cations, concentration of boron or other toxic elements, and, of particular importance to MI, the bicarbonate concentration relative to the calcium plus magnesium concentration. Calcium and iron precipitates are a potential problem. An analysis of the water source will indicate whether the carbonate+bicarbonate or iron concentration is high enough to be a problem. Typically, a carbonate+bicarbonate level higher than 100 parts per million (ppm) (mg/L) coupled with a pH above 7.5 indicates a potential problem with calcium. Iron levels higher than 0.2 parts per million (mg/L) indicate potential iron problem (table 7–2). Frequent water analyses should be carried out to determine presents of chemicals listed in table 7–1. The water should be acidified to a pH of about 6.5, as needed, and the system should be flushed frequently to prevent formation and accumulation of chemical precipitates.

Plants are adversely affected by the total water potential of the soil solution, which is mostly the sum of the matric and osmotic potentials. The advent of MI has made the use of higher salinity water possible by using high-frequency irrigation to maintain a stable and higher soil moisture (matric potential), which compensate for the higher salts (osmotic potential) in the root zone of the crops. Figure 7–14 is a diagram published in 1953 by the U.S. Salinity Laboratory for classification of irrigation waters based on electrical conductivity (EC) and SAR. This diagram gives a conservative

Figure 7–14 Diagram for the quality classification of irrigation waters



Salinity hazard

Salinity

C–1, Low Salinity—Water can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices, except in soils of slow and very slow permeability.

C–2, Medium salinity—Water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

C–3, High Salinity—Water cannot be used on soils with moderately slow to very slow permeability. Even with adequate permeability, special management for salinity control may be required, and plants with good salt tolerance should be selected.

C–4, Very High Salinity—Water is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must have rapid permeability, drainage must be adequate, irrigation must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

Sodicity

S–1, Low Sodium—Water can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium.

S–2, Medium Sodium—Water will present an appreciable sodium hazard in fine-textured soils, especially under low leaching conditions. This water may be used on coarse-textured soils with moderately rapid to very rapid permeability.

S–3, High Sodium—Water will produce harmful levels of exchangeable sodium in most soils and requires special soil management, good drainage, high leaching, and high organic matter additions. S–4, Very High Sodium—Water is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity.

version of irrigation water quality determined by the SAR and the EC of the water. Depending on the water quality, various amendments may be used to improve the quality of the water. Two types of conventional water amendments are commonly available: acids or acid forming materials and calcium salts. For example, water with a high SAR can be improved by adding gypsum, ammonium, or potassium thiosulfates, urea sulfuric acid, and others. With MI, it is important to know that when the water has high bicarbonate content, acids should be used to prevent precipitation of calcium bicarbonate.

(c) Biological factors

(1) Algae and slimes

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 aboveground. 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.

The water should be analyzed to determine bacterial and/or algae counts that are above minor concern (table 7–2). If the pH of the water is above 7.0, then chlorinate and flush. Chlorination at the end of an irrigation application is the primary means for controlling microbial activity. Residual chlorine should be measured at the end of the furthest lateral, 30 minutes after injection, and it should be no less than 2 ppm (mg/L). See NEH623.0706(f), Chlorination.

(2) Iron bacteria

When iron is present in water in the soluble ferrous (Fe^{++}) form, it is oxidized in the presence of oxygen to the insoluble ferric (Fe^{+++}) 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 ppm (mg/L) or greater, and the pH is between 4.0 and 8.5. One solution for removing iron is to aerate the water and allow the iron to precipitate. This will require sufficient aeration and reaction time, as well as a settling basin. The second option is to use chlorination to remove the iron. The chlorination section contains further information on the procedure.

(d) Combined factors

Often the physical, chemical, and biological conditions are combined, which makes the treatment even more complex. Most water quality problems found in irrigated agriculture can be managed with good filtration, selection of emitters with large orifices and turbulent flow, water acidification, frequent chlorination, and frequent flushing of the laterals.

(e) Chemical precipitation reactions

Various types of chemicals can be injected into MI systems to control calcium and iron precipitates and organic deposits. Acid is the best treatment for bicarbonates resulting from calcium and magnesium precipitation, as shown by equation 7–3. The acid should be chosen and used at a concentration that will offset the excess bicarbonates (table 7–3). Data in table 7–3 show an example of the amount of acid required as functions of the bicarbonate concentration in the irrigation water and the type and concentration of the acid. An acid concentration that maintains a pH of 6 to 7 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.

Any change in the total electrolyte concentration of the water or the relative concentration of an individual ion affects the SAR and, ultimately, the salt distribution in the soil profile. When calcium (and/or magnesium) is removed from solution by precipitation, exchange, or absorption by plants, the SAR increases (Bowman and Nakayama 1986).

Precipitation reactions can occur by:

Simple chemical precipitations:

$$Ca^{++} + 2Cl^{-} = CaCl_2 \quad \text{(eq. 7–1)}$$

$$Ca^{++} + SO_4^{--} = CaSO_4 \quad \text{(eq. 7–2)}$$

Complex chemical precipitations are pH⁻ and ionic-concentration-dependent and, in the following case, are also dependent on the partial pressure of CO^2, the various equilibrium constants and temperature.

They are much more difficult to solve:

$$Ca^{++} + 2HCO_3^{-} = CaCO_3\ (ppt) + H_2O + CO_2\ (gas) \quad \text{(eq. 7–3)}$$

In each of these cases, the Ca^{++} ion may be replaced by Mg^{++} ion, or both reactions can proceed simultaneously. In any case, the precipitation of Ca^{++} and Mg^{++} will increase the SAR and will probably decrease the soil permeability. Adjusting the pH to 7 or less will reduce the potential precipitation of $CaCO_3$. If in doubt, the Langelier Saturation Index (LSI) concept provides a systematic approach for determining the potential for $CaCO_3$ precipitation by using the pHc obtained from the Ca, HCO_3 and TDS of the water as shown in equation 7–4:

$$pH_C = \left(pK_d - pk_s\right) + p(Ca) + p\left(HCO_3\right) + p(ACF) \quad \text{(eq. 7–4)}$$

where:

K_d = the dissociation constant of HCO_3
K_s = solubility product of $CaCO_3$
p = represents the negative logarithm of the various terms
ACF = activity coefficient factor for Ca and HCO_3 (Nakayama 1968)

Table 7–3 gives an example of the amount of acid needed to neutralize 90 percent of the bicarbonates in 1 acre-foot (1,233 m^3) of water using three concentrations of N-pHURIC (urea buffered sulfuric acid). Urea buffered sulfuric acid is a common acid used in California because at the first two concentrations (N-pHURIC 28/27 and N-pHURIC 15/49), it does not require a special DOT permit, and it provides some N as urea.

(f) Chlorination

Chlorination is the primary means for controlling microbial activity in irrigation water. The chemistry and application principles for chlorination are the same as those used in swimming pools. Products include gas, solids, and liquid formulation. The chemistry of all these compounds will not be treated here. The effectiveness of chlorination is tested by measuring the concentration of free residual or available chlorine, which is the excess of active chlorine over the amount required to kill bacteria. Test kits commonly used to measure free chlorine in swimming pool can be used to test for efficacy of the chlorination system. Do not use ortho-tolidine indicators commonly used

Table 7–3 An example of the amount of urea-buffered sulfuric acid required to neutralize various concentrations of bicarbonates in irrigation waters

Bicarbonate content ppm (mg/L)	N–pHURIC* required to neutralize 90% of the bicarbonates in 1 acre-ft (1,233 m^3) of irrigation water		
	N–pHURIC 28/27	N–pHURIC 15/49	N–pHURIC 10/55
	gallon		
50	31 (117)	176 (61)	14 (53)
100	61 (231)	32 (121)	28 (106)
200	122 (462)	63 (628)	56 (212)
400	244 (924)	126 (477)	112 (424)

for swimming pools because this type of indicator only measures total chlorine, and not free residual chlorine concentration (Gilbert and Ford 1986). Apply chlorine at the end of the irrigation when the system is not fertigating. Free chlorine residuals of 2 ppm (2 mg/L) at the end of the laterals, 30 minutes after the end of chlorination, will control most biological organisms in the irrigation system. In some cases where water contains a lot of biological materials (chlorine demand), the injection of chlorine must be increased to 10 ppm by trial and error to obtain the adequate residuals of 2 ppm (2 mg/L), after 30 minutes of contact time. Acidifying the water first to pH<7.0 will increase the efficacy of the chlorination. Chlorine must be injected upstream of the filter to filter out insoluble ferric hydroxide, which may have precipitated during the oxidation of the soluble ferrous iron to the ferric form. Operators using large systems have found that chlorination with the gaseous form of chlorine is the most economical in the long run, but it also requires the greatest amount of safety precautions. Table 7–4 shows various commercial chlorine products, quantity needed to provide 1 pound of chlorine equivalent and the quantity needed to treat 1 acre-foot of water to provide 1 ppm (1 mg/L) chlorine concentration.

Sodium hypochlorite should be used to treat hard ground water supplies. Treatment with calcium hypochlorite causes calcium to precipitate. Deliberately precipitating the iron and filtering it out before it enters the pipe network can prevent iron precipitation at the emitter. 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 free chlorine residue, for example 1 ppm (1 mg/L).

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 (10 mg/L), 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 (rate of at least 10 ppm/10 mg/L) 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:

- For algae, use 0.5 to 1.0 ppm (0.5 to 1.0 mg/L) continuously or 20 ppm (20 mg/L) for 20 minutes in each irrigation cycle.
- For iron bacteria, use 1 ppm (1 mg/L) more than the ppm of iron present (varies depending on the amount of bacteria to control).

Table 7–4 Commercial chlorine products and quantities needed to treat 1 acre-ft (1,234 m^3) of water and provide 1 ppm (1 mg/L) chlorine concentration in the irrigation water (without bacterial demand)

Chemicals	Quantity equivalent to 1.0 lb (454 g) of Cl_2	Quantity to treat 1 acre-ft (1,234 m^3) to 1 ppm Cl2 (1 mg/L Cl_2)
Chlorine gas	1 lb (454 g)	2.7 lb (1,226 g)
Calcium hypochlorite		
65–70% available chlorine	1.5 lb (681 g)	4.0 lb (1,816 g)
Sodium hypochlorite		
15% available chlorine	0.67 gal (2.54 L)	1.8 gal (6.81 L)
10% available chlorine	1.0 gal (3.78 L)	2.7 gal (10.22 L)
5% available chlorine	2.0 gal (7.57 L)	5.4 gal (20.44 L)

- For iron precipitation, use 0.64 times the ferrous ion content.
- For manganese precipitation, use 1.3 times the manganese content.
- For slime, maintain 1 ppm (1 mg/L) 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.

Peroxide is another oxidant, similar to hypochlorite and becoming more common in its use. However, for treatment of irrigation systems, there are several differences. Peroxide is very effective for treatment of organic matter, complexes organic-mineral sediments, and does not appear to be harmful to plants, even in high concentration.

Common solutions are stabilized 50 percent concentration; however, in many areas, it is restricted by law. The more common concentration of 30 to 33 percent is still useful.

Peroxide is very unstable. Tiny quantities of dust or metals residues can turn a barrel of peroxide to simple water in few days. All producers add some stabilizers to keep the peroxide intact. The amount and effectiveness of those stabilizers varies. Test sticks are available to test for concentration of peroxide. For continuous treatments, redox sensors can also be used online. Both measuring methods can tell the user if there is peroxide in solution, but not about the electivity of the oxidation. The specific gravity of peroxide is higher than water, and this can be another measure to verify the content.

Peroxide requires a catalyst for oxidation: the release rate of oxygen radical from the peroxide depends on the availability of this catalyst. Iron or manganese do it perfectly. In most events, the reaction speed of the peroxide is much faster than reaction time of hypochlorite. Unlike chlorine, the release rate does not depend on the substrate content (i.e., organic matter in the driplines) but on the presence of the catalyst. Therefore, the effectiveness of the oxidation can diminish quickly downstream stream of the injection point. Injection should be done as close as possible to targeted clogging. When there is a heavy load of organo-mineral sediment, there might be a thick drift that clogs downstream drippers; in this case, precaution is needed. All manufacturer's instructions should be followed with this dangerous material.

623.0707 Fertigation

(a) Benefits

Fertigation is the process by which fertilizers are injected through MI systems to maintain real-time nutrient concentrations in a limited root zone, meeting crop requirements in space and time. With MI, little of the fertilizer spread or broadcast over the soil surface moves into the root zone, especially with drip or even more so with SDI systems. Fertigation provides several advantages over using conventional surface spreading, broadcasting and banding of fertilizers (Bar-Yosef 1999):

- Fertigation minimizes the time and space fluctuations of nutrient concentration in the root zone resulting in crop yield and quality increases.
- Accurate injection of fertilizer amounts to match specific concentrations required by crops according to crop development stages, soil characteristics, and climatic conditions is possible.
- Liquid fertilizer solutions containing concentrations of required nutrients, including minor elements that are difficult to apply accurately by conventional fertilizer application methods, can be used.
- Crop foliage remains dry, thus minimizing leaf pathogens and avoiding leaf burn sometimes associated with foliar fertilizing methods.
- The amount of soluble fertilizer amounts applied to the soil contribute to minimum leaching below the root zone and pollution of ground water is minimized.
- Selective application of fertilizers to a small portion of the soil volume enhances fertilizer use efficiency and reduces the leaching potential during periods of high precipitation.
- Microfertigation reduces the potential for runoff of fertilizers and pollution of streams and surface waters.
- Microfertigation uses the MI system to distribute fertilizers and eliminates the use of heavy equipment through the field, thus conserving energy and reducing agricultural dust.

However, microfertigation advantages are somewhat offset by the need to invest in relatively expensive injection and monitoring systems, safety devices, shipping, and storage of large volumes of liquid and diluted fertilizers.

(b) Factors affecting fertigation

The fate of fertilizers injected via fertigation is a dynamic process affected by many physical, chemical, and microbiological variables. Maintaining a balance of nutrients in the soil should be an important management objective. Among the many factors effecting the choice of fertilizers for fertigation is the affect on the pH of the water and soil solution. Irrigation water with high pH needs to be treated with acid to avoid precipitation of Ca and Mg carbonate/bicarbonate and phosphate and subsequent clogging of discharge channels and orifices of the emitters. High soil solution pH also decreases zinc, iron, and phosphorus availability to plants.

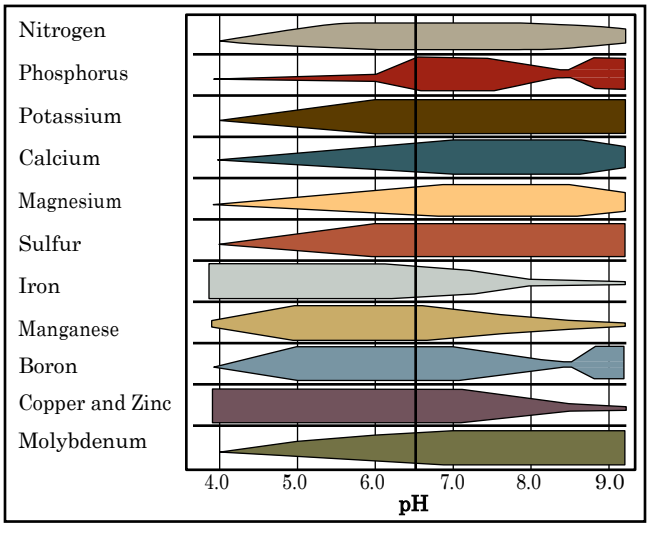
The affect of the soil pH on P-availability is also a strong function of the cations present, ranging from iron, aluminum, and maganese ions at low pH to calcium and maganese at high pH. In addition to these reactions, the amount and composition of organic matter and microorganism activity also interact with the availability of inorganic phosphorus in soil (Dean 1949). Therefore, high pH fertilizers (ammonia, urea) are not recommended for fertigation with phosphate fertilizers since they will raise the pH of the water and may cause precipitation of calcium and magnesium phosphates. In arid and semiarid regions, acids, such as phosphoric acid (H_3PO_4) and nitric acid (HNO_3), are recommended to reduce the pH of the irrigation solution because they do not increase the soil salinity. However, in cases where sulfur is needed, sulfuric acid (H_2SO_4) may be used. Lowering the pH of irrigation water below four may be detrimental to plant roots and could increase the aluminum and magnesium concentrations in the soil solution to toxic levels (Bar-Yosef 1999). On the other hand, continuous injection of low concentration of phosphoric acid, H_3PO_4, has been found to prevent root intrusion in SDI systems used to irrigate field crops.

The adopted fertilizer program must be considered in designing and managing a MI system. Some types of fertilizers are not suitable for injection because of the

volatilization of gaseous ammonia, effect on soil and water pH (fig. 7–15), low water solubility (table 7–5), separation of the components in the mixture, crop specific requirements, salt index (table 7–6), leaching losses from application with excessive water, and problems with soils and the quality of irrigation water (fig. 7–10). 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 or there is a need to modify the chemistry of the water before injecting fertilizers.

The solubility of various fertilizers in water at temperatures of 32 degrees Fahrenheit (0 °C), 68 degrees Fahrenheit (20 °C) and 122 degrees Fahrenheit (50 °C) is shown in table 7–5. When dissolving granular fertilizers in water, the diurnal temperature change may cause crystallization of the salt, so it is important to use the minimum night temperature as a reference or dilute the solution to prevent crystallization at night. Note that the solubility decreases significantly with decreasing temperature so that unused fertilizer left over from the summer may crystallize in the winter and block or break connecting pipes and injector fittings.

Figure 7–15 Typical nutrient availability in soil as affected by the soil solution pH (adapted from Bucknam and Brady 1966)



The mobility of nutrients in soil is also a factor to be considered in the choice of fertilizers to be injected in the MI system. Spatial distribution of nutrients in the soil profile will be affected by the source of fertilizer used, the soil physical characteristics, clay types, the pH and ECw of the irrigating solution, organic matter content, and the frequency of fertigation. More details will be considered in the following sections dealing with specific nutrients.

Temperature and temperature changes affect all physical, chemical, and biological reactions in the soil-plant-atmosphere system. Nutrient uptake by roots can be affected by changes in nutrient solubility, organic matter decomposition, viscosity of the solution, root membrane change in resistance as a function of temperature, nutrient release rate (low P availability in cold soil and lack of P-availability below the plow zone), and chemical transformation rate (low N-transformation rate from urea in cold soils). Hence, knowledge of soil and ambient temperatures may be valuable in determining the type and injection rates of nutrients.

The salt index (SI) is a measure of the salt concentration that fertilizer induces in the soil solution. The SI of a material is expressed as the ratio of the increase in osmotic pressure of the salt solution produced by a specific fertilizer to the osmotic pressure of the same weight of sodium nitrate ($NaNO_3$), which is based on a relative value of 100. Where the soil salinity is an important irrigation factor or when crops have a high crop-specific fertilizer requirement, fertilizers with a low SI are recommended; values lower than 100 are desired. Table 7–6 shows the effect of various fertilizer materials on the SI of the soil solution (Rader et al. 1943). For example, potassium chloride should not be used under saline soil conditions.

(c) Plant nutrients and fertilizers

(1) Macronutrients

Nitrogen (N)—Fertigation with nitrogen in microirrigation systems requires understanding of:

— the pH-dependent chemical reactions in the soil and water

— the quality of the irrigation water

— the type of fertilizer injected

Table 7–5 Solubility of common fertilizers, as affected by temperature (adapted from Bar-Yosef 1999; Lange 1967)

Fertilizer	Formula	Temp = 32 °F Solubility (lb/gal)	Temp = 0 °C Solubility (kg/m³)	Temp = 68 °F Solubility (lb/gal)	Temp = 20 °C Solubility (kg/m³)	Temp = 122 °F Solubility (lb/gal)	Temp = 50 °C Solubility (kg/m³)
Ammonium chloride	NH_4C_l	2.45	294	3.10	372	4.21	504
Ammonium nitrate	NH_4NO_3	9.87	1,183	16.27	1950	28.71	3,440
Monoammonium phosphate	$NH_4H_2PO_4$	1.89	227	2.35	282	3.48	417
Diammonium phosphate	$(NH_4)_2HPO_4$	3.58	429	4.80	575	8.85	1,060
Ammonium sulfate	$(NH_4)_2SO_4$	5.89	706	6.34	760	7.09	850
Potassium chloride	KCl	2.34	280	2.90	347	3.59	430
Potassium nitrate	KNO_3	1.11	133	2.64	316	7.18	860
Potassium sulfate	K_2SO_4	0.58	69	0.92	110	1.42	170
Calcium nitrate	$Ca(NO_3)_2$	8.51	1,020	28.46	3,410 (25)*	31.38	3,760 (99)
Phosphoric acid	H_3PO_4	———	———	45.74	5,480 (25)	———	———
Urea	$(NH_2)_2CO$	6.51	780 (5)	9.96	1,193 (25)	———	———

Number between parentheses indicates a different temperature

Table 7–6 Comparative effect of fertilizer materials on the soil solution—SI (adapted from Rader et al. 1943; Western Fertilizer Handbook 1975)

Fertilizer	Salt index
Sodium nitrate	100.0
Ammonium nitrate	104.7
Ammonium sulfate	69.0
Diammonium sulfate	29.9
Monoammonium phosphate	34.2
Potassium chloride	116.3
Potassium nitrate	73.6
Potassium sulfate	46.1
Potassium-magnesium sulfate	43.2

When steps are taken to avoid specific problems that can result from the soil, water, and fertilizer interactions, most nitrogen fertilizers may be injected with no side effects in the water or irrigation system.

Among the more common nitrogen fertilizers applied directly through microirrigation systems are:

- anhydrous ammonia (82–0–0)
- aqua-ammonia (24–0–0)
- urea (44–0–0)
- ammonium nitrate (34–0–0)
- ammonium sulfate (21–0–0)
- calcium nitrate (15.5–0–0)

Anhydrous ammonia (82–0–0), when used as an agricultural fertilizer, is compressed into a liquid. In the liquid state, it is stored in specially designed tanks. Both anhydrous ammonia and aqua ammonia can be injected into irrigation water, but the fertilizer efficiency is likely to be reduced because of volatilization.

Ammonia injection increases the pH of the solution and can cause soluble calcium and magnesium to precipitate as Ca^- and Mg^- carbonates or bicarbonates in the water. These precipitates will coat the inside of pipes and plug emitters. A high soil solution pH will also reduce the availability of boron, iron, magnesium, zinc, and phosphorus (fig. 7–15).

The calcium and magnesium precipitation problem can be managed 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 and does not improve the availability of boron, iron, magnesium, zinc, and phosphorus to the plants.

Urea (44–0–0) is a soluble nitrogen fertilizer. Urea liquid fertilizer has a pH of about 8, and when hydrolysis occurs, it increases the soil pH even more so that urea injection with phosphate fertilizers can be problematic. Urea and ammonium nitrate can be 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.

Most of the nitrogen salts and urea dissolve readily in water (table 7–5) although one must keep in mind the effect of temperature on solubility.

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 nitrate (34–0–0) has a very high solubility (16.27 lb/gal; 1,950 kg/m3 at 68 °F). Ammonium sulfate (21–0–0) has a solubility of 6.34 pounds per gallon; 760 kilogram per cubic mile at 68 degrees Fahrenheit. Both are very common nitrogen fertilizer materials. In the former, about 26 percent by weight of the fertilizer is ammonium nitrogen and 8 percent is nitrate nitrogen; in the latter, all the nitrogen is in the ammonium form. Calcium nitrate $\{Ca(NO_3)^2\}$ is the most soluble of all nitrogen fertilizers (table 7–5).

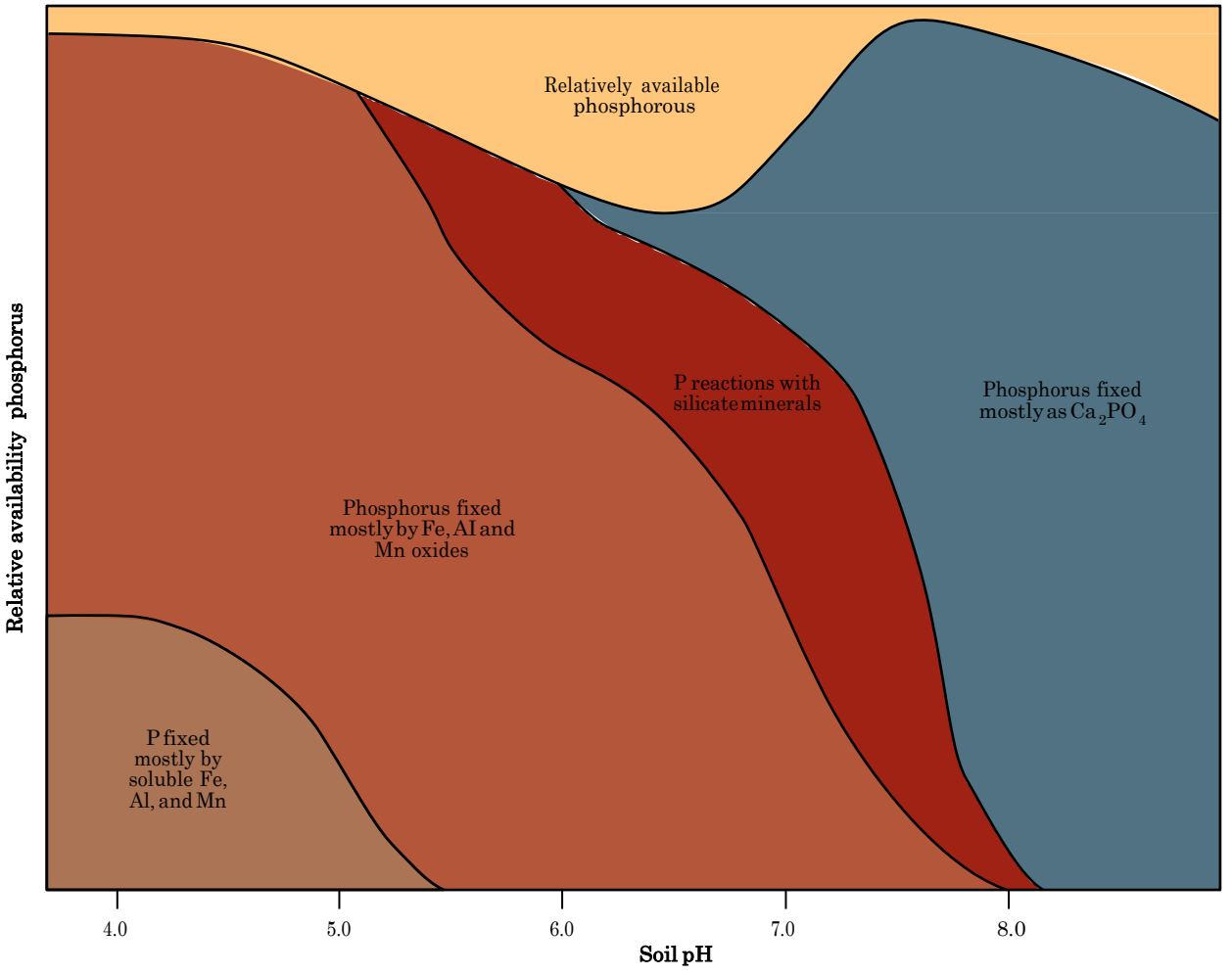
Both urea and nitrate nitrogen stay in solution in the soil and move with the soil water; these materials are highly susceptible to leaching if excessive water is applied.

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. Cation exchange reactions are very rapid, and 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 9.2), 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—In general, plants are inefficient P-users, but several factors affect the P-avilability. One of these is the pH of the soil as shown in figure 7–16. The P-availability in soil is also usually restricted to the top

Figure 7–16 Relative availability of added phosphorus in soil as affected by soil pH (adapted from Buckman and Brady 1966)



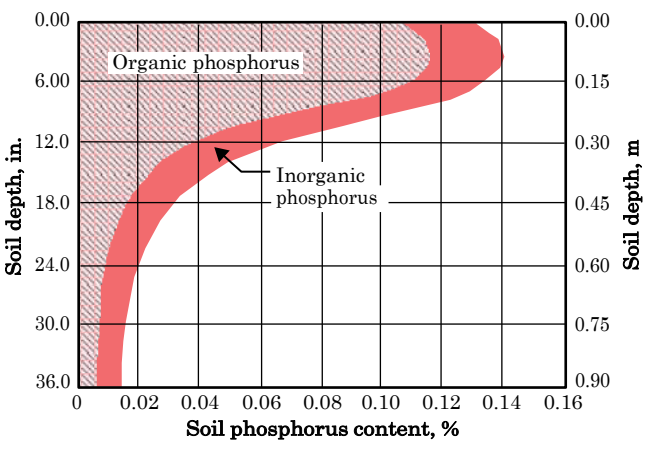
soil (fig. 7–17) and is not readily available at low soil temperatures. Hence, frequent P-fertigation is extremely important to maintain adequate concentration gradients in space and time and assure optimal plant growth, quality, and yield. This is particularly true with SDI because of the more concentrated root zone located deep below the soil surface around the emitters (Phene and Phene 1987).

With microirrigation, the use of phosphoric acid (H_3PO_4) is often recommended because of its high solubility (table 7–5) and its greater mobility in soil (Rolston et al. 1979; Bar-Yosef 1999; and Ben-Gal and Dudley 2003). Phosphorus mobility in the plant is generally high due to the transient nature of many compounds.

Other phosphorus materials are more difficult to use and apply by injection. Treble-superphosphate (TSP, 0–45–0), commonly used, is classified as water soluble, but 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) may be suitable for injection when nitrogen and phosphorus are needed.

Figure 7–17 Typical distribution of organic and inorganic phosphorus with depth in clay loam soil



The quality of the irrigation water must be considered before injecting phosphorus into a MI system. If the irrigation water has a pH above 7.5 and a high calcium or magnesium or bicarbonate 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 MI 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.

Depending on the pH status, phosphorus may be relatively immobile in soil because it becomes insoluble almost as soon as it contacts calcium or magnesium in the soil. Therefore, phosphate applied by MI collects at the soil surface or at the point of application and is unavailable to the crop. Subsequent crops will benefit, however, because the next plowing will mix the fertilizer throughout the plowed layer (fig. 7–17).

Potassium (k)—Potassium is taken up by plant in its ionic form (K^+) and can be easily injected through a MI system as potassium chloride (KCl), potassium sulfate (K_2SO_4), and potassium nitrate (KNO_3) (table 7–7). In terms of detrimental salt load and SI level (table 7–7), potassium nitrate is best and will also provide a low nitrate nitrogen (NO_3–N) concentration at the end of the season. The fertilizer moves freely into the soil and, depending on the soil texture, may not be readily leached away. Excessive application and concentra-

uptake and cause deficiency of other cations.

(2) Secondary plant nutrients

The function of secondary plant nutrient in plants is metabolic and structural.

Calcium—Calcium (Ca) is usually abundant in soil except under very acid conditions where liming is required. Hence, calcium fertigation is rarely practiced

nitrate is highly soluble (table 7–5) and can be easily injected through MI systems.

Magnesium—Magnesium (Mg) is usually abundant in soil, although, less than calcium, and excessive magnesium can induce potassium deficiency. Hence, magnesium fertigation is rarely practiced except for a few foliar applications.

Sulfur—Sulfur (S) is usually deficient in western soils. Sulfuric acid (H_2SO_4) or liquefied gypsum ($CaSO_4$) are commonly used fertigation materials to provide S to correct sulfur deficiencies. Because sulfuric acid is extremely corrosive and requires special transportation permits, fertilizer products formulated by combining urea and sulfuric acid (N-pHURIC) are recommended for injection with microirrigation.

(3) Micronutrients

The micronutrients (in alphabetical order)—boron, chlorine, copper, iron, manganese, molybdenum, and zinc can be applied through MI systems. However, application rates must be based on careful soil and water analyses and accurate metering injectors because the range between deficiency and toxicity is narrow (Western Fertilizer Handbook 1975). Trace elements applied in excessive quantities can react with salts in the water and be toxic to plants. Yet, adequate plant growth and yield cannot be achieved in the absence of micronutrients. Chelated micronutrients are often used to prolong the stability and availability of micronutrients in water and soil. If complete details for injecting trace elements into a MI 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. As shown in figure 7–16, maintaining the pH of the soil solution between 6 and 7 will maximize the availability of micronutrients.

(4) Fertilizer/chemical handling safety

Properly formulated fertilizers and chemicals can be uniformly and safely applied by injection into water through a properly engineered irrigation and injection system. In addition to the fertigation process described, irrigators can also apply herbicides, insecticides, fungicides, nematicides, and other chemicals through MI system. This process is defined as chemigation. Three types of electro-mechanical devices must be used to provide the necessary safety of the water supply:

- backflow prevention devices to prevent flow of the mixture of water and/or chemicals in the opposite direction of that intended
- check valves to provide positive closure, which prohibits the flow of materials in the opposite direction of normal flow when the operation of the irrigation system fails or is shut down
- interlock devices to ensure that the injection system will stop if the irrigation pumping plant stops and vice versa (for more details, see ASAE EP409.1 Feb 2003)
  - Federal and State laws may regulate the use of any pesticides in a manner inconsistent with the labeling. Contact local and State regulatory officials for specific regulations and requirements related to fertigation/chemigation activities.
  - Employees performing fertigation/chemigation functions should be properly trained and made aware of the safety requirements. Some States require certified applicator license.

Table 7–7 Comparison of some chemical properties of major K-fertilizer sources for fertigation (adapted from American Society of Agronomy 1985)

K fertilizer source	Chemical formula	% use	% K content	Solubility (lb/gal)	Salt index*	Detrim. salt load (lb/lb/acre/yr)**
Potassium chloride	KCl	95	51.6	1.05	116.0	0.48
Potassium sulfate	K_2SO_4	4	41.9	0.25	46.1	0.54
Potassium nitrate	KNO_3	<1	36.9–38.2	0.51	73.6	0.01

* Sodium nitrate = 100
** Detrimental salt load is the sum of Na^+, Cl^-, and $SO_{4=}$

— Bulk chemicals should be stored separately in secured facilities and properly labeled.

— Storage tanks and fittings must be compatible with the chemical solution and properly secured and labeled.

— Safety showers or ample water supply, protective clothing, respirators, and related devices must be nearby and available.

— Primary stock dilutions should always be made by adding the chemicals to the water; never add water to chemicals unless the directions specify otherwise.

— Backflow prevention, check valves, and interlock devices should be designed according to local requirements and properly used and maintained.

— The injection pump should be electrically linked with the primary water flow system to ensure that chemicals are not injected into the system when water is not flowing.

— Chemical supply containers should be protected from water flowing back into the tanks to avoid overflow of the chemical solution from the storage tanks.

— Chemicals should be injected separately, unless there is a good reason to do so and with knowledge that any reactions occurring between the injected chemicals will not harm the system, particularly the emitters.

623.0708 Components of a MI system

The components of a microirrigation system can be grouped into the following general categories:

- control head
- mainlines, submains, and manifolds
- emitters
- flushing system

Depending on system type, site topography, soil characteristics, crop, water/fertility requirements, water availability, and water quality, field systems may vary considerably in physical layout. A typical layout of a microirrigation system with the general categories is shown in figure 7–18. A more detailed layout with listed components is shown in figure 7–19.

The control head—The control head delivers water from the source to the mainline. It must control the amount and pressure of water delivered, filter that water to a level that will not cause operational problems, and add fertilizer and chemicals to the water in precise amounts.

The control head typically has the following major components:

- pumping station
- control and monitoring devices
- fertilizer and chemical injectors
- filtration system

In addition, the control head contains appurtenances needed to control and monitor flow rate and pressure of irrigation water.

Mainlines, submains, and manifolds—The mainline, submains, and manifolds receive irrigation water from the control head and deliver it to the lateral and emitters. The proper design of the mains, submains, and manifolds ensures that pressure loss through these conduits does not adversely affect operation of the system. Appurtenances also are found on mains, submains, and manifolds.

Figure 7–18 Typical MI system layout *(courtesy F.R. Lamm and Kansas State University)*

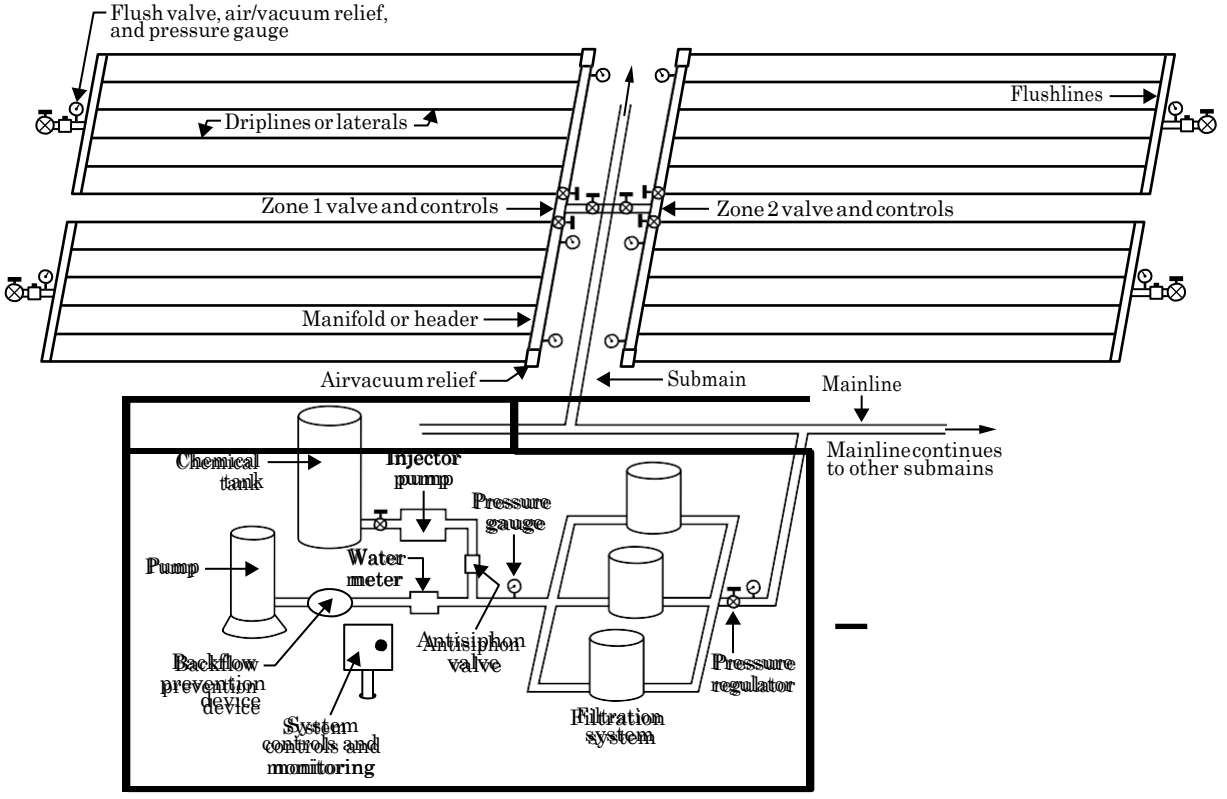
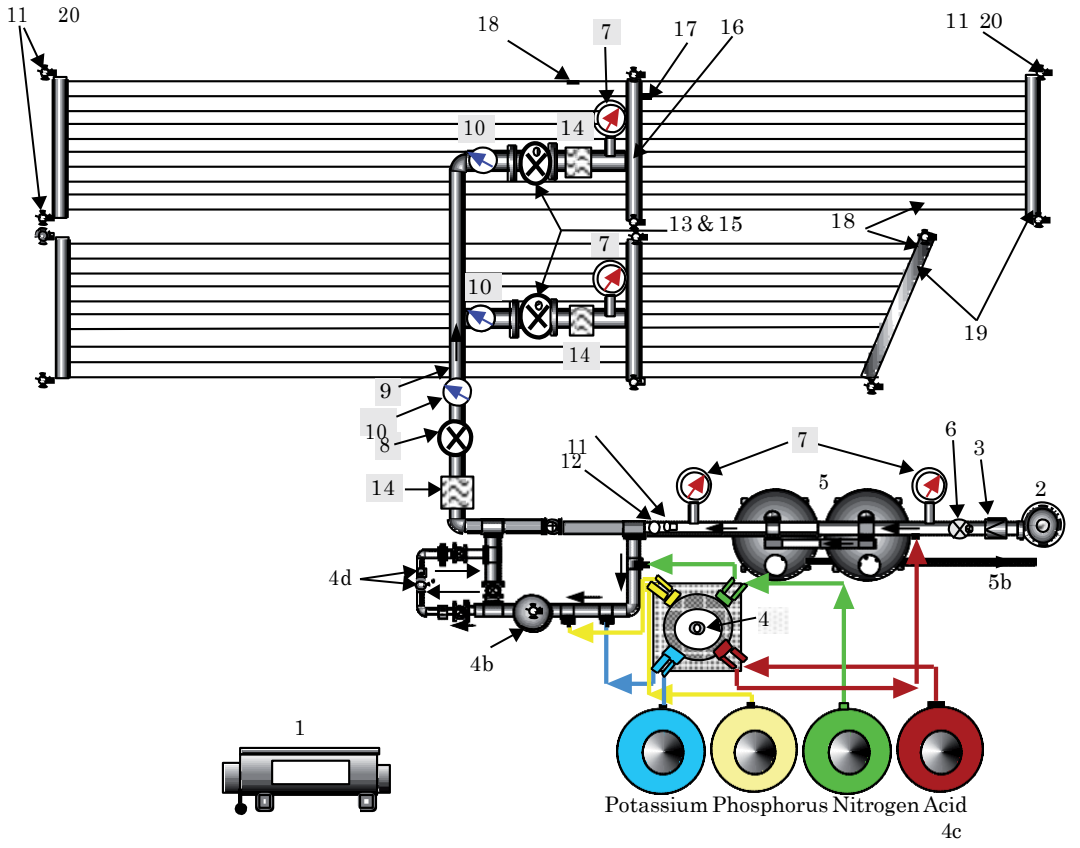


Figure 7–19 Detailed layout of typical MI system components



1. Control System (automation)
2. Pump
3. Back flow prevention valve
4. Fertilizer injector/fertilizer mixing tank (4b)/fertilizer tanks (4c)/pH and ECw meters (4d)
5. Filter tanks/Backwash exhaust (5b)
6. Pressure sustaining valve
7. Pressure gauges/transducers
8. Mainline control valve
9. Mainline
10. Flow meter (totalizing and submain)
11. Air vents at high points, after valves and at ends of lines
12. Pressure relief valve
13. Field control valve
14. Submain and secondary safety screen filter
15. Pressure regulating valve
16. Submain
17. Lateral hookups
18. Laterals/emitters
19. Flushing manifolds
20. Flush valves

Laterals and emitters—Irrigation water is delivered to the plant from emitters, which are located on the lateral. Both can be located aboveground (e.g., on a trellis), on the ground, or below the soil surface.

Flushing system—Proper maintenance of a microirrigation system requires regular flushing. Individual mains, submains, manifolds, and laterals should be designed so they can be flushed properly. The control head must be able to supply water at a velocity high enough to dislodge and move sediment from the pipelines.

(a) The control head

(1) Pumping station

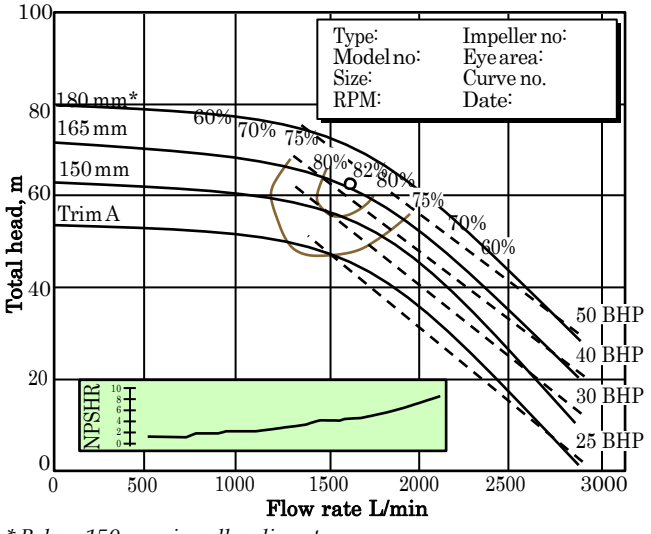
The pumping station consists of the power unit (internal combustion engine or electric motor) and a centrifugal, deep-well, or submersible pump and appurtenances. In the design and selection of pumping equipment for a MI system, high efficiency is the principal requirement. Some MI systems require a pumping unit to deliver water on-demand to the system at the required pressure. Centrifugal pumps are often used for this purpose. Centrifugal pumps operate over a wide range of operating conditions but are limited by the suction lift (theoretically, 33 ft (10 m) at sea level, but in practice, about 23 ft (7 m)), and they need to be primed.

Graphical characteristic curves define the operation of these pumps in terms of the discharge, the head, the size of the impeller, and the horsepower. They are available from the manufacturers and usually provide head-capacity curves, efficiency curves, horsepower curves, and net positive suction head required (NPSHR) curves. Figure 7–20 shows a hypothetical characteristic pump curve that can be used to select and accurately design pumping systems. The pump operating range should be selected based on the number of operating subunits and their flow rate, either individually or collectively, the estimated peak crop water requirements, and the total system head to maintain the required emitter operating pressure. Figure 7–21 shows a pumping station using a low head centrifugal pump. Design details are addressed in NEH623.0712, Sample Designs for Microirrigation. For more information on pumps, see NEH Section 15, Chapter 8, Pumps.

(2) Control system

Basic automation—Methods for controlling irrigation systems should answer two questions: when to irrigate (timing) and how much to apply (quantity) (Howell et

Figure 7–20 Theoretical pump curve and efficiency variable used for design purpose



* *Below 150 mm impeller diameter select Trim A or others*

Figure 7–21 Pumping station using a low head centrifugal pump

al. 1984). These decisions are critical to the management of any irrigation system and even more critical with MI where the key principle is to maintain a relatively a small soil volume at nearly constant soil moisture by frequent application of small amounts of water. Control methods range from manual control valves to fully automated, computerized feedback control systems. Methods can be classified in three groups:

- sequential operation (manual operator required)
- partial automation (volumetric valves, time clock, sequential valve control but no instrumental or feedback inputs—some level of human intervention needed)
- full automation computerized control systems (multiple input and feedback measurements and variable output controls based on inputs—system operates without human intervention)

Philip (1969) stated that to fully understand and be able to predict irrigation water requirements accurately, the soil-plant-atmosphere continuum (SPAC) must be considered as a physically integrated dynamic system in which transport processes occur interactively. A monitoring and control system based on feedback measurements of plant and soil components and real time measurements of meteorological variables as well as hydraulic system inputs can make it easier to maximize water use efficiency and productivity (Phene et al. 1990). Depending on the enterprise level of sophistication, the crop type, the irrigation method, and the price and availability of the water, either of these control methods may be used. However, a fully automated system is almost a necessity for high-frequency irrigation of one or more waterings per day that are sometimes used with microrrigation.

Sequential operation—Parts of the system can be operated manually or 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 manually 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 microirrigation. Volume can be controlled most simply with some automation by use of volumetric or mechanical time clock 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 time clock valves are used.

Full automation—Operation can be fully automated by using a central controller operated on a time or volume basis or based on soil-moisture or plant water stress sensing or by estimating Et_c using a weather station reference ET_o, or a National Weather Service Class A evaporation pan and a crop coefficient. In either case, automation will require 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 either at the control panel, automatically or by remote computer entries. Rather than using a fixed-cycle interval for the system, each irrigation cycle can be started by one or a combination of sensors. Electronic soil moisture sensors in the plant root zone can be used to activate the controller to open and close the valves. Various types of electronic soil moisture instruments have been used as the soil moisture sensor (tensiometers, Boyoucos blocks, heat dissipation sensors, soil psychrometers, and TDR probes). 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. MI systems automatically controlled by soil moisture are not widely in use because of the technical problems associated with the uneven distribution of micro-level moisture. A better approach uses a feedback from the rate of change of several soil moisture sensors to adjust a crop coefficient rather than the actual soil moisture measurements (Phene et al. 1990). The logic of a system capable of performing these functions automatically is shown in figure 7–22, and the typical components for

a remotely accessible, automated, real-time/feedback control system are shown in figure 7–19.

The overall control system consists of automated, real-time Data Acquisition and Control System (DACS) modules, the monitoring and control software, the input instrumentation (ET data, soil moisture sensing, wind speed, water flow and pressures, temperature, and precipitation) and the three-way output controls (solenoid valves, filter backwash, and fertilizer injection). The electronic components of the DACS are shown in figure 7–23.

(3) Fertilizer/chemical injection

After the benefit of accurate water application, controlled injection of chemicals and fertilizers is the most important benefit of MI systems. Substances commonly injected into MI systems include fertilizers, chlorine, acids and approved fungicides, herbicides, and pesticides. This section describes the components used for fertigation and chemigation. Use of injection system for treating irrigation water and fertilizing crops is described in NEH623.0706.

Precision application of high-quality fertilizers is especially important and can improve crop response to essential nutrients while using less fertilizer than traditional irrigation methods. Microfertigation can also efficiently fertilize crops that are covered by plastic mulch.

Injection equipment should be located downstream of the pump. In some cases, acids should be injected upstream of filters, which aid in mixing and can prevent emitter plugging due to particulate buildup or chemical precipitation. However, strong acids may corrode filter components unless they are made of acid resistant materials such as stainless steel (316 or better) or fiberglass composites and epoxy-coated metals. Severe plugging can occur to drip systems from unpredictable mixing of water, fertilizers, and chemicals that may form precipitates (see NEH623.0706 for criteria and recommendations about mixing chemical/fertilizers with water). When in doubt, have a water quality analysis performed to help recognize and address potential incompatibilities.

Figure 7–22 Logic for a remotely accessible and real time/feedback automated control system *(courtesy of BCP Electronics)*

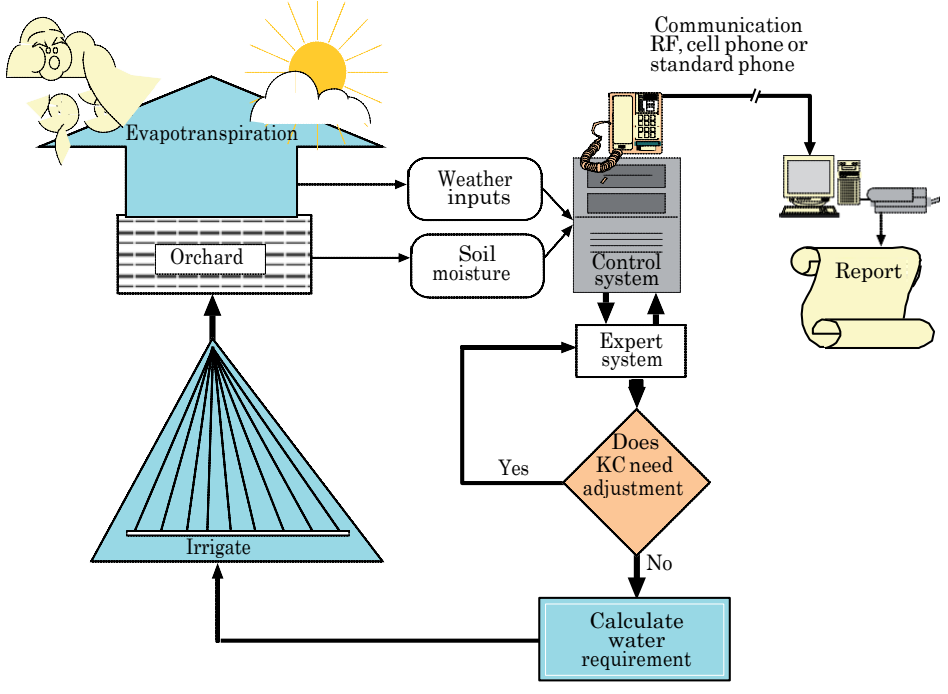
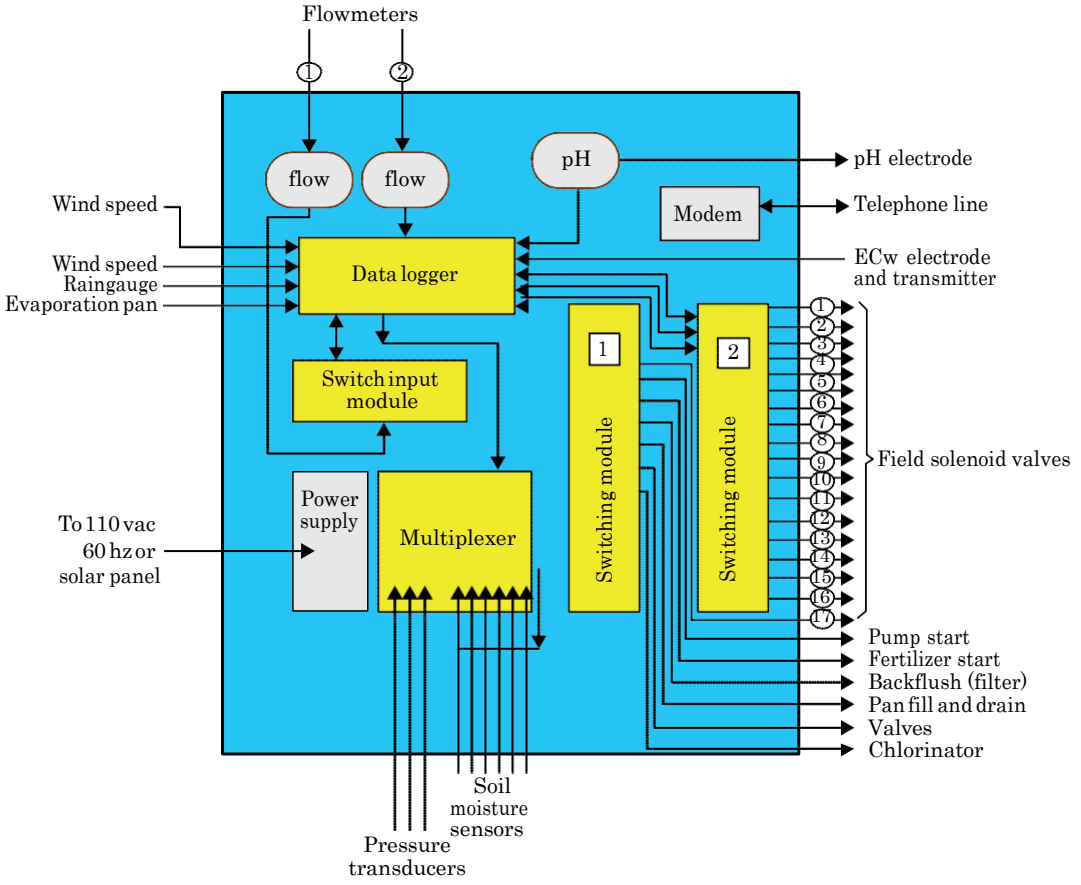


Figure 7–23 Schematic of components for a large remotely accessible, a real time/feedback automated control system *(courtesy of BCP Electronics)*



Automated control system panel *(courtesy of Jerry Walker)*

When specifying and/or installing injection equipment:

- Comply with all Federal, State, and local regulations.
- Obtain a permit if required, and hire a dealer with knowledge and competence in the fertigation/chemigation practices.
- See NEH623.0707 and for basic recommendations.
- Test the compatibility of the chemical to be injected with the irrigation water using a jar test, which is a simple test of precipitation risk, before injecting any chemicals/fertilizers to a MI system.

Highly concentrated acids and other corrosive chemicals are commonly injected into MI systems. The components of the injection system, such as tubing, gaskets, and fittings, should be made from suitable materials. While PVC and other commonly used materials are highly resistant to diluted acids, concentrated acids can degrade them over time. Chemicals should be injected into the center of the water flow in the mainline or in a mixing chamber, so that the chemical will be diluted before it makes contact with the inside wall of the pipe. Tubing and fittings made from polyvinylidene fluoride plastic (such as KYNAR) will be resistant to concentrated acids and other chemicals used in irrigation systems. **Caution**: Never inject acid into aluminum pipe.

There are many types of injectors to choose from (fig. 7–24a–d). Table 7–8 summarizes the features of some common injection equipment, and table 7–9 gives chemical and temperature resistance of common materials used in MI systems.

Table 7–8 Type of common chemical injection equipment and features

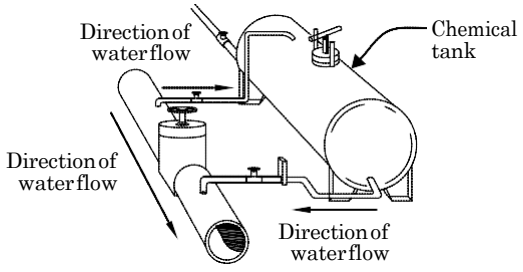
Type of injector	Function	Remarks
Pressure differential tank (fig. 7–24a)	A pressure differential generated by a valve or other hydraulic restriction forces water into a tank containing the chemical. The chemical mixes with the incoming water, exits the tank and reenters the water main downstream of the restriction	a. Relatively simple b. Requires a significant pressure drop in the mainline c. May not mix water and chemicals properly unless baffles are installed in the tank d. Does not control injection rates and the initial concentration is higher than the final
Gravity tank (fig. 7–24b)	A tank located above the canal or water storage drips the chemical into the water at a preset rate	a. Simple b. Allows some control over injection rates c. Requires a chemical resistant float valve and metering valve
Venturi (fig. 7–24c)	Water flowing through a narrowing pipe accelerates and creates a vacuum which pulls chemical into the water path (application of the Bernoulli principle)	a. Allows a relatively good control of the injection b. A 10–30% drop in pressure drop is caused by the friction in the venturi c. Can use a small pump to reduce the loss of pressure
Metering pump (fig. 7–24d and 24e)	Many types of metering pumps are available; some require electrical power and others used water pressure	a. When maintained properly, allows accurate and precise control of injection rates. b. Some pumps are flow-proportional

Table 7–9 General chemical and temperature resistance of various types of nonmetallic materials used in filtration systems, pumps, laterals, emitters, and various headworks components

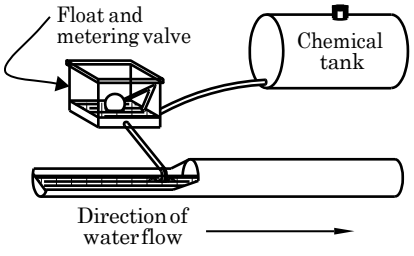
Material	Resistance	Maximum Permissible Temperature (Water)	
		Constant	Short term
Polyvinyl chloride (PVC. UPVC)	Resistance to most solutions of acids, alkalis and salts and organic compounds miscible with water. Not resistant to aromatic and chlorinated hydrocarbons	60 °C 140 °F	60 °C 140 °F
Chlorinated polyvinyl chloride (CPVC)	Can be used similarly to PVC but at increased temperatures.	90 °C 195 °F	110 °C 230 °F
Polypropylene (PP)	Resistance to water solutions of acids, alkalis and salts as well as to a large number of organic solvents. Unsuitable for concentrated oxidizing acids	60 °C 140 °F	80 °C 175 °F
Polyvinylidene (PVDF)	Resistance to acids, solutions of salts, aliphatic, aromatic and chlorinated hydrocarbons, alcohols and halogens. Conditionally suitable for ketones, esters, ethers organic bases and alkaline solutions	90 °C 195 °F	110 °C 230 °F
Polytetrafluroethylene (PTFE)	Resistant to all chemicals	140 °C 285 °F	150 °C 300 °F
Nitrile rubber (Buna-N)	Good resistance to oil and gasoline. Unsuitable for oxidizing agents	90 °C 195 °F	120 °C 250 °F
Butyl rubber ethylene propylend rubber (EPDM, EPR)	Good resistance to ozone and weather. Especially suitable for aggressive chemicals. Unsuitable for oils and fats	90 °C 195 °F	120 °C 250 °F
Chloroprene rubber (Neoprene)	Chemical resistance very similar to that of PVC and between that of Nitrile and Butyl rubber	80 °C 175 °F	110 °C 230 °F
Fluorine rubber (Viton)	The best chemical resistance to solvents of all elastomers	150 °C 300 °F	200 °C 390 °F

Figure 7–24 Chemical injection method

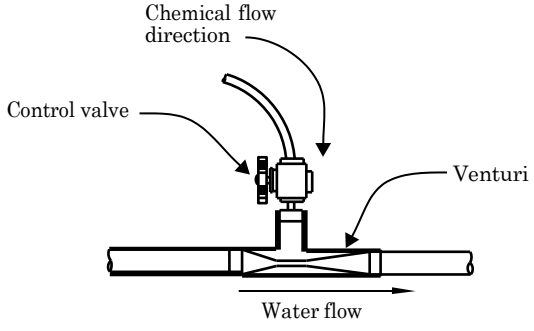
(a) Chemical injection method using a pressure differential tank



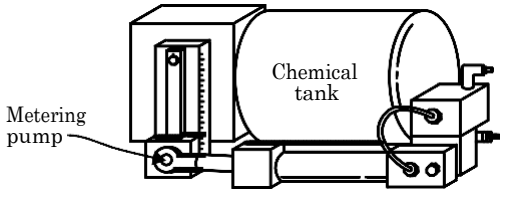
(b) Chemical injection method using a gravity-feed tank with a metering float and valve assembly.



(c) Chemical injection method using a venturi with a control valve assembly



(d) Chemical injection method using a metering pump with control valve assembly



(e) Chemical injection method using a water-driven metering pump assembly

Differential pressure—Differential pressure can be used to inject chemicals into the irrigation water. Figure 7–24a shows a differential pressure injection system. The chemical tank is under the same pressure as the mainline. Valves or venturi pipe sections can be used to create a significant pressure loss. Pressure differential injection systems have no moving parts, require no external power source, and are less expensive than pump injectors. Their main disadvantage is that the chemical solution to be injected must be contained in a tank at the same pressure as that in the mainline (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 replenishing service.

The gravity tank system—The gravity tank system (fig. 7–24b) is normally used in an open water flow system, such as a canal or ditch (preferably lined). A tank located above the water structure is equipped with a float and metering valve assembly that regulates the discharge of chemical into the water at a preset rate. Since no pressure or power is required, it is a simple, low labor-intensive method, which can use less expensive parts than a pressurized system. However, it requires a chemical resistant float and metering valve.

Venturi system—The venturi effect (Bernoulli principle) is obtained by narrowing the inlet pipe diameter and then gradually expanding it back to the inlet diameter size; this is usually a carefully designed molded piece of plastic or metallic pipe. 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 7–24c shows the components of a venturi tube type pressure differential injection system.

Pumping with metering pumps—Pumping with metering pumps (fig. 7–24d and 7–24e) is the most versatile and accurate method for injecting chemicals into MI systems. Positive-displacement piston pumps can be designed and calibrated to give an accurate constant or variable injection rate, but they must be properly and regularly 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 (fig. 7–24e) 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 to a reservoir.

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 small 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 shut-off valves are available for water-driven pumps, and automatic time controllers are available for electric-driven pumps. Letting the chemical tank run dry can stop injection, but this practice may damage the injector pump unless it is shut off. When automation is used as described in the control system section (fig. 7–22), the metering of the fertilizer is programmed for injection during the middle of the irrigation cycle to avoid the line filling time of the irrigation cycle. Injection of chemicals can also be stopped during filter flushing operations. Continuous measurements of pH and ECw are used to ensure adequate system performance and to control the pump on or off to avoid accidents and malfunctions.

Suction of chemicals—Suction of chemicals through the intake side of a pump is a simple injection method, although not recommended for MI systems because of safety concerns and because 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.

One of the primary benefits of microfertigation over other fertilizer application methods is the accurate control of application rate. In addition, the effectiveness of chlorine, acid, and other chemicals depends greatly on concentration. As a result, it is important to design an injection system that allows good control over injection rates. Pressure differential tanks, in particular, are not recommended where accurate control of injection rate is required. The specific

injection method to be selected will depend on the irrigation system design and materials to be injected. The operational and design equations for calculating injection rates, concentrations and tank capacities are described (Keller and Karmeli 1974).

Injection rate:

$$q_f = \frac{F_r A}{F_c \times T \times H_r} \qquad \text{(eq. 7–5)}$$

where:

q_f = injection rate of liquid fertilizer solution into the system, gal/h, (L/h)
F_r = rate of fertilizing (quantity of nutrient to be applied) per irrigation cycle, lb/acre, (kg/ha)
A = irrigated area per irrigation cycle, acre, (ha)
T = time of irrigating per cycle (h)
F_c = concentration of nutrient in the liquid fertilizer, lb/gal, (kg/L)
H_r = ratio between fertilizing time and irrigation time, usually taken as 0.8 to allow time to flush the system

Fertilizer concentration:

$$F_c = \frac{K F_r}{H_r d_i} \qquad \text{(eq. 7–6)}$$

where:

F_c = fertilizer concentration, ppm (mg/kg)
K = 4.414 for English units (100 for metric units)
d_i = depth of irrigation water required, in (mm)

Tank capacity:

$$C_t = \frac{K F_r A}{F_c} \qquad \text{(eq. 7–7)}$$

where:

C_t = tank capacity, gal (L)
K = 0.11988 for English units (1.0 for metric units)

For irrigation systems using a pressure differential or a venturi injection device, the fertilizer tank should provide enough capacity for fertilizers to be injected in a complete irrigation.

Fertilizers should be injected over a period of time, which allows maintenance of a reasonably uniform distribution, and they should be injected early enough during the irrigation cycle to allow the water to flush the system free of chemicals before shutting down.

(4) Filtration

The main purpose of filtration is to keep mainlines, submains, laterals, and emitters clean and working properly. Maintaining clean emitters is as important to a MI system as water is to crops. The common sources of emitter clogging were addressed in NEH623.0706. Physical, chemical, and biological clogging factors can and must be prevented by proper filtration and water treatment.

Factors affecting the selection of a filtration system—Filtration equipment is a critical component of MI systems, and good filtration equipment is the heart of any MI system. Designers should choose the correct equipment for the specific farm water source. There are several types of filter systems available. The choice of an adequate filtration system should be based on careful consideration of the following factors:

- a thorough analysis of the water supply including particle size, chemical, and biological concentrations
- filtration requirements for the specific emitter used
- seasonal or other changes in potential contaminants
- potential for precipitation of dissolved solids due to chemical reactions.
- consultation with a qualified water and irrigation specialist
- the anticipated types and concentrations of chemical/fertilizers to be used and their effect on filter parts

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 and light, slow-moving, or still water will 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 may be

needed to control algae and bacteria. Municipal and/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 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. In the absence of manufacturer data or recommendations, it is recommended that filtration systems be designed to remove solids equal to or larger than a tenth of the emitter opening diameter 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 inside of laminar flow emitters along the walls where the flow rate is zero, even during operation. The clogging results may not be rapid, but it is inevitable. Table 7–10 summarizes some of the most common types of filter, their functions, major specifications, and their proper use.

Sand media filters—Sand media 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. 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 sand media filter unless the 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 media filters are water quality, types and size of sand media, flow rate through the filter, and allowable pressure drop. Although they are more expensive than comparable screen filters, sand media filters can handle larger loads with less frequent backflushing and a smaller pressure drop. Sand media 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 most often used in MI systems are designated by numbers. Table 7–11 compares the media most commonly used.

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 gallons per minute per square foot (14 L/s/m^2) of bed; this value has been established relative to a given bed composition and filter use. If the water supply is excessively dirty, the flow rate should be reduced to 10 to 15 gallons per minute per square foot (6.8–10.2 L/s/m^2). On the other hand, conditions for microirrigation might be such that rates of about 30 gallons per minute per square feet (20.4 L/s/m^2) may be allowed. Figure 7–25 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.

Selecting the smallest medium possible for a given installation is a common practice; 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. The maximum recommended pressure drop across a sand media filter is about 10 psi (0.70 kg/cm). The pressure differential trigger should be set for 5 to 7 psi over the clean filter pressure difference. 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. In addition, the filters should be backflushed a minimum of once per day to prevent small particles of sand from working down through the sand bed and slowly plugging up the

Table 7–10 Summary of the most common types of filters, their functions, and their recommended uses

Type of filter	Applications	Function	Specifications	Remarks
Sand media	a. Required for any open or surface water sources where large amounts of organic matter are present b. Frequently used with well water	Fine sand particles within two or more closed tanks create a three-dimensional filtering surface trapping algae, slimes and fine suspended solid particles. Tanks are back-flushed one at a time, while remaining units continue filtration	a. Filtration from 200 mesh (74 μm) to 600 mesh (25 μm) b. Tank sizes are typically ranging from 12–48 in–diameter (0.30–1.20 m) c. Recommended using at least three tanks	a. Cleaned by back-flushing b. Stainless steel epoxy-coated or fiberglass tanks are available for acid injection c. Several tanks can be used in parallel for large flow rates
Screen	a. May be used as a primary filter for clean water sources b. Can be a safety back-up downstream from the sand media filter c. Can be used as a submain secondary field filter	a. Fine mesh screen(s) enclosed in one or more pressurize tanks traps organic and inorganic particles. b. Filter can be cleaned manually or automatically by various high pressure rotating water jets and/or brushes	Available screen materials and mesh varies based on manufacturers and types of filter; common sizes: 50–200 mesh (300–74 μm)	a. Cleaned by manual removal or automatic flushing while using rotating water jets b. Can be easily clogged by organic contaminants
Disk	Use for primary filtration similar in application to media filters	a. Filters through densely packed thin color-coded polypropylene disks that are grooved diagonally on both sides to a specific micron size (fig. 7–28) b. The flushing process starts automatically when given pressure differentials or time setting are reached; flush commands from the controller	a. Commonly available disks range in sizes: 18–600 mesh (800–25 μm) b. Multiple filter configuration adjustable to water quality and capacity demands	a. Flushing commands are sent from the electronic controller b. Flushing is rapid and water efficient c. Stacked filter do not require a lot of space d. Disks should be replaced annually unless not processing a lot of dirty water
Gravity-flow	a. Used for low levels of particulate matter. b. Used to deliver a large volume of water at low pressure	Water falls on a screen separator, which traps particulate matter, which is then washed out into a collection tank	Available from 100 to 200 mesh (150–74 μm)	a. Cleaned by water flow and additional spray nozzles. b. Booster pump is usually necessary after this filter
Centrifugal sand separator	a. Used to remove sand and other inorganic particles b. Used as a prefilter to help reduce back-flushing of main filter	Centrifugal action creates a vortex that pushes away particles heavier than water, removes well casing scale, sand and other inorganic particles	Removes particles heavier than water down to 200 mesh (74 μm) b. Works with a 5–7 lb/in^2 (0.35–0.49 kg/cm^2) pressure loss	a. Self-cleaning b. Low maintenance c. Does not remove organic matter d. Is not 100% effective-usually used as a prefilter

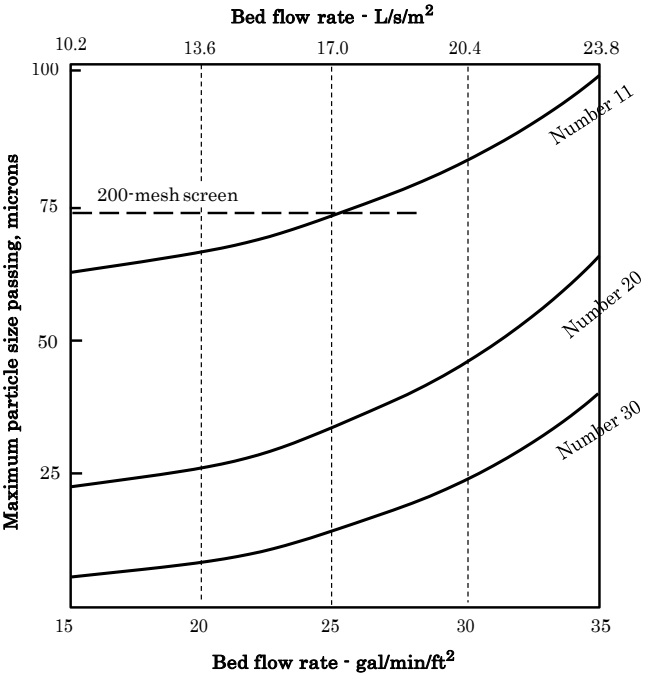
Table 7–10 Summary of the most common types of filters, their functions, and their recommended uses—continued

Type of filter	Applications	Function	Specifications	Remarks
Suction screen	For prefiltration at pump intake in ponds or reservoirs or lakes	Coarse screen traps debris, birds, and fish; preserve foot-valve pump	Available in 10–30 mesh (1500–500 µm)	Cleaned by rotating inner water jets
Settling basin	Prefilter to remove silt or other inorganic particles	Allows silt and clay particles to settle; may also provide aeration to remove dissolved solids and iron in suspension	Sized based on peak water budget and particulates types and load	Cleaned by draining and removing build up; outlet must be away from inlet; must control algae

Table 7–11 Comparison of sand media filter and screen mesh equivalent

Sand media designation	Mean effect media size microns	Screen equivalent
#8 crushed granite	1900	100–140
#11 crushed granite	1000	140–180
#16 silica sand	825	150–200
#20 silica sand	550	200–250
#30 silica sand	340	250–

Figure 7–25 Effect of flow rate on the maximum particle size passing through a typical free-flow sand filter with media of various sizes



bottom of the sand media filter. A timer or a pressure switch that senses the pressure differential across the medium can activate automatic backflushing.

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 gallons per minute per square foot (6.8 to 10.2 L/s/m^2) per bed for numbers 30 and 20 media and between 20 and 25 gallons per minute per square foot (13.6 and 17.0 L/s/m^2) per bed for numbers 16 and 11 media. Care must be taken to ensure sufficient pressure and time to perform an adequate backflush. Three- or four-sand media tanks may be required if backflushing is performed during irrigation. The tanks that are not being backflushed must be able to filter water for the irrigation demands as well as the backflushing operation and stay under the maximum flow rate per unit area for the filter. Testing to ensure the backflushing duration is adequate should be conducted periodically. The backflush water should be clear at the end of the cycle. Schematics of a sand media tank in the filtration mode and in the backflushing mode, respectively, are illustrated in figure 7–26.

Sand media filter-filtration process—Unfiltered water enters filter tank through a three-stage distributor plate and reaches the media bed with minimal turbulence. Contaminants are entrapped as the water flows through the media bed. Collectors in the underdrain create uniform collection of the filtered water. During filtration, head loss across the filter media will increase as solids accumulate within the media. When the pressure differential limit set by the hydraulic conditions of the system is reached, the media will be cleaned of the accumulated solids by the backflush operation.

Sand media filter-backflushing process—Periodic backflushing is necessary to cleanse the media bed of accumulated contaminants. During the back-flushing process, the flow of clean, filtered water from one or more tanks in the system is reversed through one filter at a time via a three-way backflush valve. As the flow is reversed, the media bed is floated via hydraulic turbulence, and contaminants are flushed out to the backflush manifold through the backflush port of the three-way valve. The design of the underdrain system is critical to ensure uniform floating of the media bed during the backflush process and for minimizing the amount of backflush water required (three is highly recommended) to rapidly expel the contaminants from the media bed. Once the backflush is completed, the valves return to the filtration mode and the next filter will backflush. A minimum of two tanks is required so that the system can continue to operate during the backflushing operation.

Backflushing of any type of filter requires a significant amount of water; provisions must be made to dispose or store flush waters. When a storage reservoir is used to supply irrigation water, flush water can be returned to this reservoir to allow particulate matter to settle. Care should be taken to locate the filter discharge outlet as far back from the irrigation water intake as possible. In cases where there is no irrigation storage reservoir, a flush water storage reservoir should be constructed to accommodate the flush water and recycle it for irrigation. Figure 7–26c shows a small three-tank stainless steel sand media filter station used for drip irrigation.

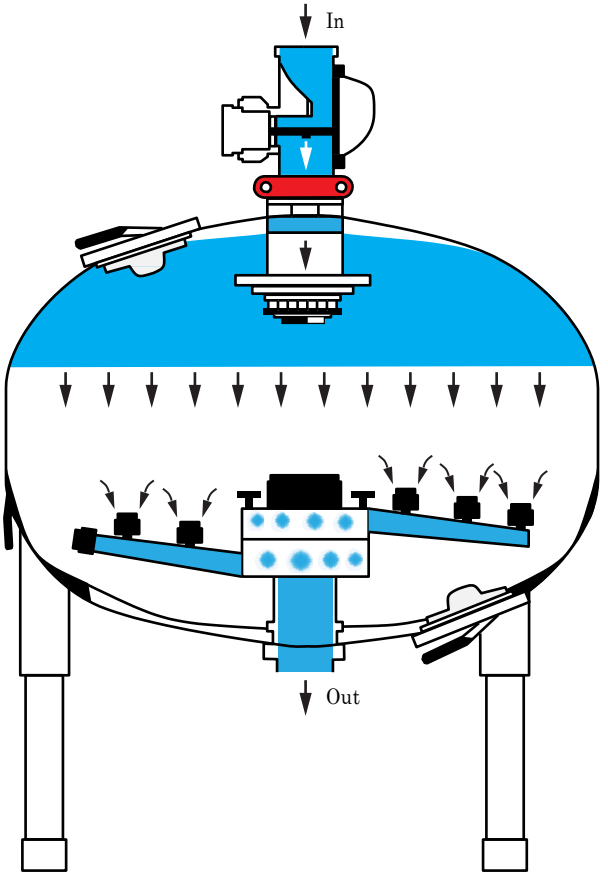
Screen filters—In screen filters, the hole size and the total amount of open area determine the efficiency and operational limits. The basic parts of a screen filter are the filter screen and basket. The screen is stainless steel, nylon, or polyester mesh. Moderate amounts of algae tend to block the 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 backflushing 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.

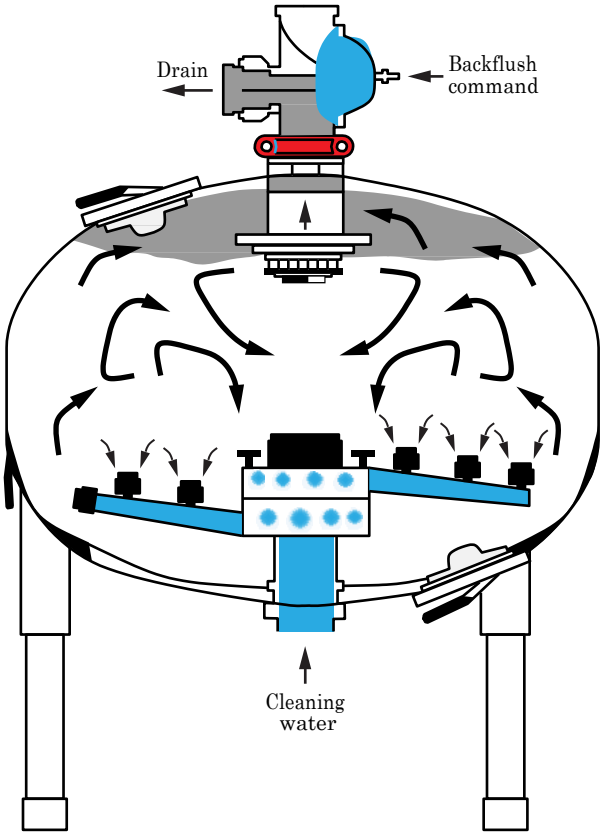
A screen filter should be cleaned when the pressure head loss is about 3 to 5 psi (0.21 to 0.35 kg/cm^2) or at a fixed time determined in advance. The most common methods of cleaning are:

Figure 7–26 Schematic of a sand media filter

(a) Filtration mode



(b) Backflushing mode



(c) A small, three-tank sand media filter

- manual cleaning, i.e., pulling out the filter basket and cleaning it by washing
- by repeated washing, i.e., washing the filter basket by backflushing or otherwise washing (blowing off) the basket without dismantling the filter
- 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 mainline breaks. A small amount of sand or organic particles large enough to clog the emitters could ruin them.

The head loss in a clean filter normally ranges between 2 and 5 psi (0.14 and 0.35 kg/cm^2), 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 (0.35 and 0.70 kg/cm^2).

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 gallons per minute per square foot (136.0 L/s/m^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 gallons per minute per square foot (27.2 and 68.0 L/s/m^2) of total screen area, depending on the percentage of open area. Examples of screen filters are shown in figures 7–27 through 7–29.

Disc filters—In a disk filter, thin color-coded polypropylene disks are grooved diagonally on both sides to a specific micron size. The disks are then stacked and compressed on a spline. When stacked, the grooves on top run opposite to the grove below, creating a filtration element with a statistically significant series of valleys and traps for solid particles (fig. 7–30). The stack of disks is enclosed in a corrosion and pressure-resistant housing. Disks are available from 18 mesh (800 microns) to 600 mesh (25 microns).

During the filtration process, the filtration disks are tightly compressed together by the power of the spring and the differential pressure of the water, thus providing high filtration efficiency. Filtration occurs while water is passing from the outer diameter to the inner diameter of the element. Depending on the micron rating of the disks, there are from 18 (in 400 micron disks) to 32 (in 20 micron disks) stopping points in

Figure 7–27 A basic, manual-flushing, in-line screen filter that can be used as a field secondary filter

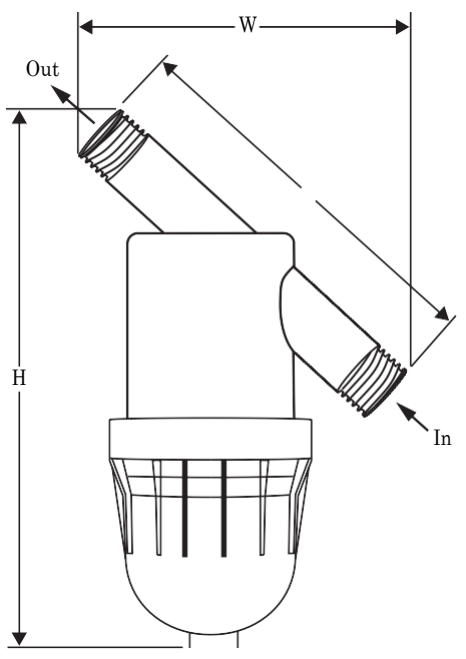
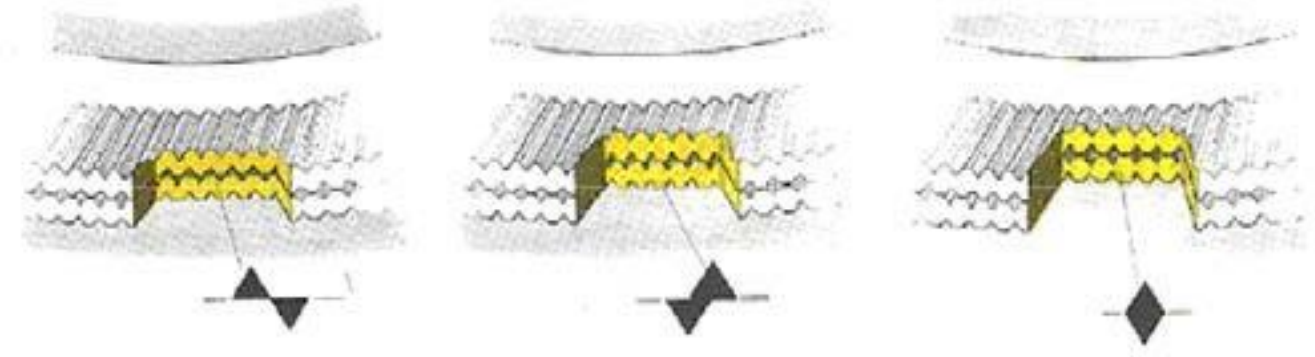


Figure 7–28 A large-diameter, steel, in-line screen filter

Figure 7–29 A battery of automatic flushing screen filters

Figure 7–30 Schematic of the grooves creating a filtration element with a statistically significant series of valleys and traps for solid particles



each track, thus creating the unique in-depth filtration. Disk filters are available in various configurations to accommodate needed filtration and flow requirements. Three types of commonly used disk groove patterns are shown in figures 7–30.

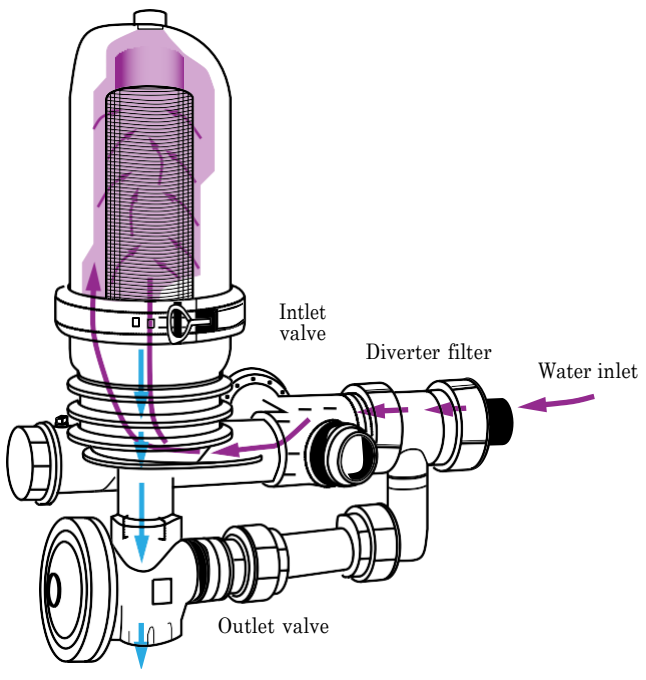
The flushing process starts when a preset pressure differential or time setting is reached; electronic flush commands are sent from the controller to three separate components in the filter:

- The inlet valve starts its flush mode (entrance closed, drain opens).
- The outlet valve starts its flush mode (downstream closed, flush water diverter opens).
- The filter starts its operational mode (stack of discs enters open mode). Water flows via the diverter filter screen, through the diverter into the outlet-flushing valve. It enters the main filter (which is open), where jets of water flush the grooves in the discs as the discs spin. The water carries away impurities from the discs toward the inlet valve. At the end of the flushing process (20 seconds) the flush command is withdrawn, the discs are tightened again and the filter returns to the filtration mode. The inlet and outlet valves return to the filtering mode. Water flows once again into the filter, carrying with it the impurities that are collected on the diverter filter screen during flushing. Figure 7–31 displays filtering and backflush modes for a disk filter. Figure 7–32 shows a typical disk filter installation.

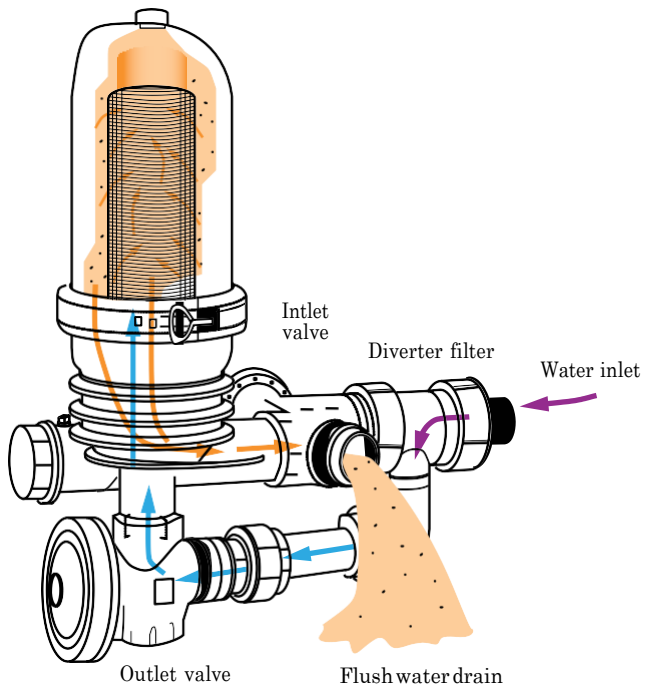
Gravity-flow filter—Gravity-flow filters are primarily used to deliver a large volume of water at low pressure. They have been used to remove organic slimes and some low level of particulate matter. Figure 7–33 schematizes the filtration process; water from the

Figure 7–31 Schematic of a disk filter shown in filtration and backflush mode

(a) Filtration mode



(b) Backflush mode



inlet tank falls on a screen, which traps contaminants, which then wash out into the trash collection tank. The filtered water is collected in the catch tank and then flows by gravity to the irrigation system. Depending on the pressure requirements of the irrigation system, a booster pump may be required downstream of this filter. Filters are available from 100 to 200 mesh (152–74μm). Figures 7–34 and 7–35 show a typical gravity-flow filter and water flowing in a typical gravity-flow filter, respectively.

Centrifugal sand separator—Centrifugal (vortex) 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.

Figure 7–32 A battery of three automated disk filters

Figure 7–33 Schematic of a typical gravity-flow filter

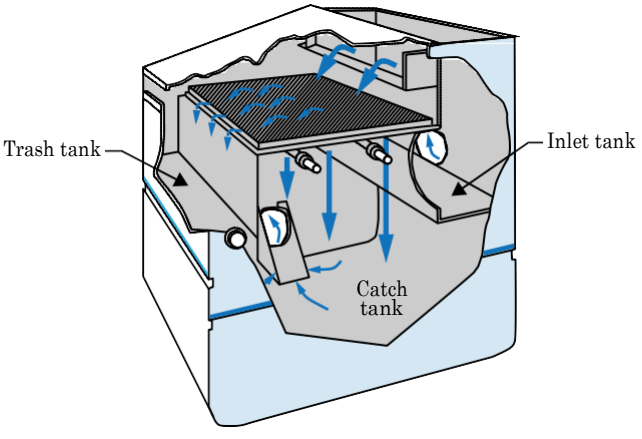


Figure 7–34 A typical, large capacity gravity-flow filter

Figure 7–35 Water flowing over the screen in a gravity-flow filter

Although vortex separators do not remove all the required particles, they are efficient for ejecting large quantities of very fine sand, such as a well that is bringing up sand. A screen filter downstream to catch contaminants that may pass through, especially during startup and shutdown should always back up the separator. Figure 7–36 shows a three-unit vortex sand separator system, to the left and ahead of the three disk filters.

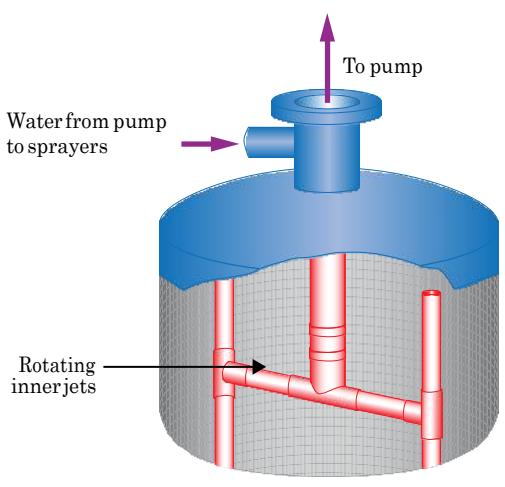
Figure 7–36 A three-unit vortex sand separator system (to the left of disk filters)

Vortex separators do not operate well with varying flow rates. This poses a problem for irrigation systems that have zones of varying flow rates. The operating range for vortex separators is a 5 to 11 psi (0.35 to 0.7 kg/cm^2) of pressure loss. If the pressure drop is much less than 5 psi (0.35 kg/cm^2), the flow rate is too low, and there will be insufficient centrifugal force to settle out the particles. If the proper flow rate is maintained, the pressure drop will remain constant.

Suction screen filters—Suction screen filters are used for prefiltration at pump intake in reservoirs, ponds, or lakes. They are essential if pumping from an open water source to prevent debris from causing malfunction of foot valves or damage to pumps. They use a relative coarse screen, 10 to 39 mesh (1500–500 µm). They are cleaned from the inside by constantly rotating inner water jets or the screen can rotate and be sprayed off from the outside. The filter and pump intake should be installed 1 to 2 feet (0.30–0.60 m) below the water surface, but not close to the bottom of the reservoir. Figure 7–37 shows the top section of a suction screen filter, with its rotating inner cleaning jets exposed and the top section of a rotating suction screen filter, with its outer cleaning jets spraying debris off.

Settling basin—A settling basin can be an effective, economical solution to two types of water quality problems: suspended solid removal and iron removal.

Figure 7–37 Self-cleaning screen filters



Rotating inner cleaning jets

Outer cleaning jets spraying debris off

- Suspended solid removal—Turbid surface waters high in suspended sand, silt, and clay particles will require filters to backwash frequently, thus decreasing their efficacy. A well-designed and managed settling basin can remove the majority of the contaminants and serve as an effective primary filtration unit.
- Iron removal—In many underground aquifers, low water temperatures and high pressures favor the solution of carbon dioxide, which forms carbonic acid when dissolved in water. Carbonic acid lowers the pH and may cause iron to dissolve in the water. When ground water is pumped to the surface and aerated, the simultaneous decompression of the water and increase in temperature allows the carbon dioxide to diffuse into the atmosphere. Because of this, the pH of the water will increase causing the iron to oxidize and precipitate. Iron can be allowed to settle out of the water before it enters the irrigation system.

The design of the shape and size of the settling basin involves several variables that must be considered prior to starting: settling velocity of the particles, the inflow rate of the water, detention time of the water, inlet and outlet design, and space available. For example, a reservoir that can be drained and is long and narrow makes it easier to remove trapped sediments. The intake to the irrigation system should be as far as possible from the water entering the reservoir to allow as much time for settling as possible. The basin can, if needed, be lined with a plastic liner or with bentonite to avoid percolation losses of water. A maintenance program to control algae, weeds, and animals and removal of sediments should be defined and carried out. Figure 7–38 shows a well-maintained settling basin; although not lined with a plastic liner, algae and weeds are under control.

(b) Appurtances

(1) Valves

Various types of valves are used in MI systems to protect and control the irrigation system: air and vacuum relief, flow control, pressure regulation, pressure sustaining, and safety. Valves come in various design, sizes, materials, and configuration, manual or automatic, metal or plastic, and hydraulically or electronically controlled. They are manufactured in a variety of materials such as plastic, iron, brass, bronze, and aluminum and are available with a variety of connections such as threaded, grooved, and flanged. Valves for MI application range in size from 3/4 to 12 inches (19–305 mm). Optional accessories are available such as solenoids of various voltages, orifice sizes, two- and three-way pilot valves, hydraulic relays, diaphragms, and springs. Valves should be as maintenance free as possible, highly accurate for regulating pressures and reliable. Table 7–12 list valve types, their control functions, and applications. Valves should be chosen based on performance factors such as friction loss, maintenance, accuracy, reliability, durability, speed of closing/opening, flow range, pressure reduction ratio, simplicity, and cost. Valves needed at the headworks depends upon the method of operating the MI system. Figure 7–19 shows valves for a system with fertilizer and chemical injection, backflush control valves, backflow prevention, and safety controls.

On-off control valves—On-off control valves can be operated manually or electrically by using a solenoid to control the flow of water in the mainline. A three-

Figure 7–38 A well maintained settling basin

Table 7–12 Some of the valve types available for irrigation, their features, and functions

Valve type	Control functions	Applications	Remarks
Manual "on-off"	3-way manual selector permits selection of open or closed	Use with any small MI systems	
Electric control "on-off"	3-way solenoid valve, activated by an electric current or pulse to open or close valve		
Pressure reducing	Valve maintains a preset pressure, regardless of pressure or flow variation	Protects MI system from high pressures and surges	
Pressure sustaining/ relief	Valve maintains upstream (inlet) pressure, regardless of flow rate variations	Valve will close if the inlet pressure drops below the set point. It fully opens when the upstream pressure exceeds the set point	Install downstream of filter to maintain filter pressure when filter banks are backwashed
Quick relief safety valve	Opens instantly when pipeline pressure exceeds safe level. Valve closes slowly when pressure returns to normal		
Pump control valve	The electrically activated valve opens gradually on pump start-up and closes slowly before the pump is switched off	Eliminates damaging surges caused by pump start-up and shut-off	Valve operates as a non-slam check valve, preventing reverse flow
Three-way filter backflush	Acts as a main valve for filter and as a flushing valve for backwash	Used with most filtration systems requiring backflushing	Valve is usually a part of a modular filter configuration
Check/backflow preventing	Enable flow in one direction. When flow starts the flap rises. When the flow stops the flap is returned by the spring to its sealing position	Required for systems using municipal water or when pumping from aquifer and chemicals are injected	
Modulating float control	The main valve is controlled by a float valve, located in the tank or reservoir at the maximum water level	The valve maintains a constant water level	Used to maintain a constant levels in standpipes and tanks
Air/vacuum relief valves, also known as kinetic air valves, large orifice air valves, vacuum breakers, low-pressure air valves and air relief (not release) valves	Air valves discharge large volumes of air before the pipeline is pressurized, especially at pipe filling. They admit large quantities of air when the pipe drains and at the appearance of water column separation	They admit large quantities of air when the pipe drains and at the appearance of water column separation	
Air release valves are also known as automatic air valves, small orifice air valves, continuous acting air vents, and pressure air valves.	Valve continues to discharge air, usually in smaller quantities, after the air vacuum valves close, as the line is pressurized	Releases air continuously when the lines are pressurized	
Combination air valves, also known as double orifice air valves	Fills the functions of the two types of air valves described above	Admits and releases large quantities of air when needed and releases air continuously when the lines are pressurized	

way manual selector allows the choice of open or closed. Three-way solenoid valves are activated by a current or pulse (latching solenoid) that open or close the valve to allow water flow (fig. 7–39). These valves are available in various sizes, designs (globe, angle, or wye) and materials (plastic, brass, and iron) and connections (threaded, grooved, or flanged).

Pressure reducing/regulating/sustaining valves—Solenoid controlled, pressure regulating valves consist of the basic on-off control valves and a pressure reducing pilot. Pressure is reduced downstream of the valve to a preset level, which is maintained constant, regardless of fluctuating upstream pressure and flow rate.

Figure 7–40 shows a two-way solenoid controlled, pressure regulating valve. In two-way control system, the upstream side is connected by control tube to the downstream side of the valve. There are two flow restrictors, a needle valve and a pilot valve. The relative opening of the two valves determines the downstream pressure. Two-way valves are very accurate and fast responding. The disadvantage of the two-way is the considerable pressure loss even when fully opened and the need for clean water to prevent the restrictors from clogging. A three-way pilot is also available and is used when pressure loss through the valve is a concern. Three-way valve are also less likely to plug in cases of dirty water.

Solenoid controlled, pressure sustaining valves consist of the basic valves and a three-way pressure sustaining pilot. Pressure is sustained at the upstream of the valve to a preset level, while the valve outlet drains excessive pressure to maintain the preset inlet pressure of fluctuating downstream pressures and flow rate. Pressure sustaining valves are used to maintain adequate backflush pressure during filter backflush on hilly terrain, to maintain pressure in elevated areas, and many other applications where sustained pressure is necessary.

Quick relief safety valves—Quick relief safety valves are designed with to open wide passages and quickly relieve pressure at a manually preset pressure level. When normal pressure returns, they usually close slowly to prevent water hammer. They are designed to protect pipelines and other equipment from accidental high pressure events. These valves are usually supplied in thick metal such as bronze to withstand potential cavitation.

Pump control valves—During pump start up, operation, and shut-off of pumping plants, pressure and flows change very quickly and often. Quick relief valves do not respond quickly enough to the fluctuations to protect the system from water hammer. Sophisticated pump control valves may be used to regulate the rapid increase in pressure and flow rates

Figure 7–39 On-off control valve electrically operated using a solenoid

Figure 7–40 Solenoid controlled, pressure regulating valve

in pumping plants that cannot be managed by quick relief valves.

Check/back flow prevention valve—A backflow prevention valve prevents water, chemicals, and other contaminants from flowing backward from the irrigation system into the water supply. There are several types of backflow prevention devices using various mechanical designs to operate. Many States require the use of backflow prevention valves, especially when MI systems are used for fertigation and chemigation. Figure 7–41 shows a wafer style check valve in the closed position.

Air valves—Air valves are a critical component of any hydraulic network. In its natural liquid state, water contains 2 percent to 3 percent of dissolved air. As water temperature rises and/or pressure in the line drops, this dissolved air is released from the water in the form of small bubbles. The air bubbles expand and rise to the top of the pipe and accumulate at elbows and high points in the system. If not released, air pockets are formed, reducing the effective diameter of the pipe. Because air is compressible, it stores energy and reacts like a spring, causing local water hammer. If not released, air can cause pipes and fittings to burst. Under vacuum conditions, the pipe has the potential of collapsing. When using pipes with gaskets, soil particles can be ingested under the gaskets, and when the pipes are pressurized again, a leak may occur. The gaskets themselves can be sucked into the pipe, resulting in major water leaks and/or in infiltration of mud and pollutants. The resistance to water flow along the air layer can be much higher than the resistance along the walls of the pipe, especially when the air moves in a direction opposite to the flow of water.

Figure 7–41 Spring loaded swing check valve in the closed position *(courtesy of A.R.I. Flow Control Accessories)*

The use of air release valves is the most efficient way to control air in irrigation systems. Control of air is very important and, depending on the circumstances, both the presence of air and its absence can cause severe problems and damages to the system.

There are several problems associated with the presence of air in pipelines that can cause damages:

- impedance of flow in pipelines—obstruction up to complete stoppage
- serious friction losses resulting in energy losses
- water hammer damage to pipes, accessories, and fittings
- inadequate supply of water to sections of crops caused by obstruction to flow and accumulation of pressure losses at the ends of systems
- inadequate water supply to crops due to inaccurate meter and automatic metering valve readings
- serious damage to spinning internal parts of meters, metering valves, sprinklers, and sprayers
- corrosion and cavitation
- physical danger to operators from air-blown parts and from very strong streams of air, discharging at high velocity

There are several problems associated with the absence of air, when and where it is needed:

- vacuum enhanced problems and damages
- ingestion of soil particles into the drippers, a critical problem with SDI systems.
- suction of seals and gaskets, in-line drippers and other internal accessories of pipes, into the pipelines
- uncontrolled suction of injected chemicals or fertilizers into the system

- pipe or accessory collapse due to sub-atmospheric (negative) pressures
- absence of an air cushion can increase the damages of surge and slam occurrence

There are three stages of operation of an irrigation system when air handling is critical:

Stage 1 When the system starts up the pipe network is full of air. As water enters the network, air must be exhausted quickly so the water can displace it.

Stage 2 During normal operation of the system, dissolved air is released from solution, and this free air accumulates in the high locations and must be released.

Stage 3 At the end of the irrigation cycle, when the pump is stopped and/or when the system is drained, vacuum conditions may occur in the network, and air needs to be allowed to quickly enter the system.

There are three major types of air vents:

- Air/vacuum relief valves, also known as kinetic air valves, large orifice air valves, vacuum breakers, low-pressure air valves, and air relief (not release) valves. Large volumes of air are discharged before a pipeline is pressurized, especially at pipe filling. Large quantities of air are admitted when the pipe drains and at the appearance of water column separation. Figure 7–42 shows a typical air/vacuum relief valve.
- Air release valves are also known as automatic air valves, small orifice air valves, continuous acting air vents, and pressure air valves. These vents continue to discharge air, usually in smaller quantities, after the air vacuum valves close,as the line is pressurized. Figure 7–43 shows a typical air release valve.
- Combination air valves, also known as double orifice air valves, fill the functions of the air/vacuum relief valves and air release valves, admitting and releasing large quantities of air when needed and releasing air continuously when the lines are pressurized. Figure 7–44 shows a typical combination air valve.

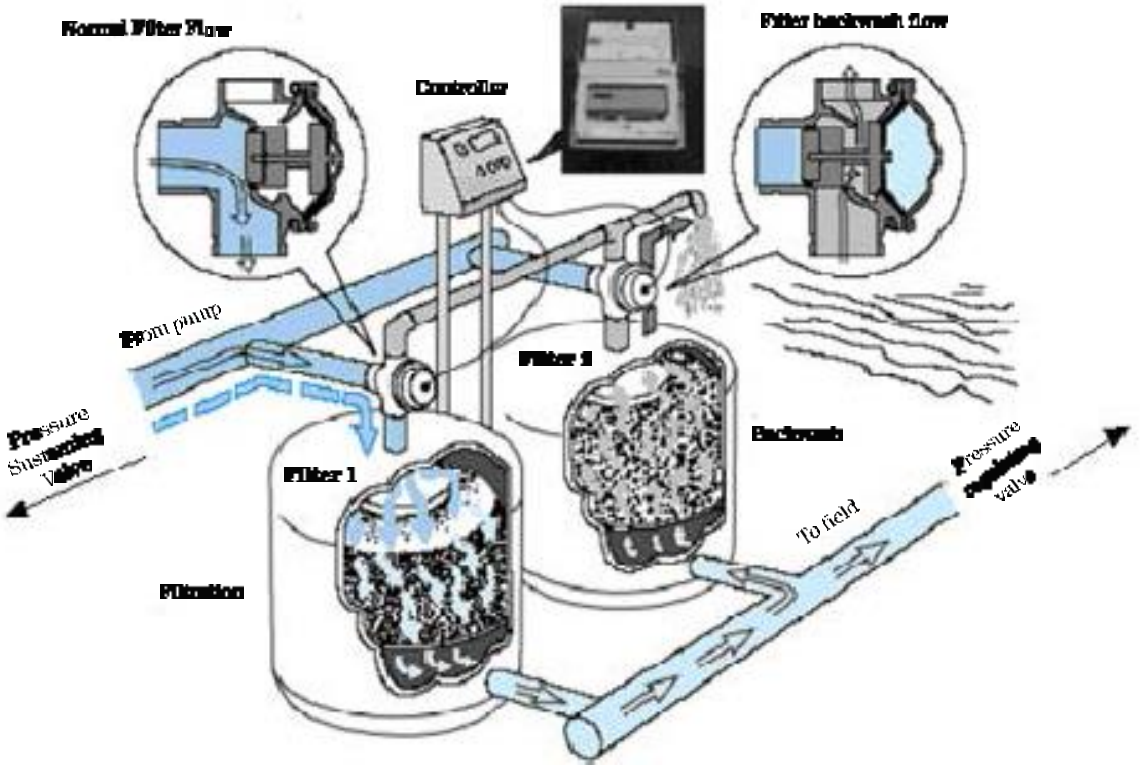
Figure 7–42 Air/vacuum relief valve

Figure 7–43 Automatic continuous acting air release valve

Figure 7–44 Combination air valve

Backflush valves to control filtration systems—Backflush valves are designed to backflush filter systems. These valves are usually a part of a modular filter configuration to ensure that filtered water is used for backflushing. Figure 7–45 is a schematic of water flow in a sand media filter backflush process showing the various valves used to control the backflush process while continuing to irrigate. Inset for filter number 1 shows the valve opening for the normal filter flow. Water is filtered through the sand media and flows to filter number 2 in the reverse direction while continuing to irrigate the field. This is made possible by the use of a pressure sustaining valve (not shown) ahead of the station, which maintains constant flow and pressure to the system and the pressure regulating valve (not shown), which continues to regulate constant pressure in the field. Inset for filter number 2 shows the filter backwash flow being exhausted to a settling reservoir for future reuse. It is recommended that fertilizer injection be discontinued during the backflushing of the filters to avoid biological growth in the reservoir. In multifilter tank systems, the above process is repeated sequentially.

Figure 7–45 Schematic of the backflush process in a typical sand media filter station



(2) Flowmeters

An important device for measuring water movement between the water source and the field is the flowmeter. Close monitoring and accurate recordkeeping with this device will allow the irrigator to make fundamental adjustments to the operation of the MI system and detect problems before they can have serious effects on the crop. Flowmeters can either be monitored manually or automatically by computerized monitoring and control systems.

A key requirement of operating a MI system is knowing how much water is being supplied to the field and the crop. In-line flowmeters may register total flow in standard volumetric units such as gallons, cubic feet, acre-feet, or others. Some flowmeters turn off automatically when a certain amount of water has been applied. Flowmeters allow the irrigator to directly measure application rates, either manually or electronically via computers with remote communication. These instruments can help detect problems such as clogging or line breakage. At least one flowmeter should be installed on the main supply line to indicate the total amount of water being applied to the field. This meter should be read during each irrigation to calculate the flow rate and total amount of applied water. This information should be recorded for each irrigation or on a regular basis. Flowmeters are available that show both total and instantaneous flow rates.

There are several types of flow meters to choose from, the most popular being the propeller-type flow meter because of its reliability and low cost. Paddle wheel flowmeters are also widely used because of their low cost. The reliability of flow measurements is highly dependent on the flow meter location. Mechanical flowmeters, such as the propeller type, assume laminar flow in the pipe. Flowmeters should be installed according to manufacturer's recommendation. In absence of recommendations, flowmeters should be installed downstream from a straight, unobstructed length of pipe at least 10 times the pipe diameter in length and followed by a straight, unobstructed length of pipe, of at least 5 times the pipe diameter. For accurate readings, the pipe must be flowing full. Figures 7–46 and 7–47 show a typical in-line recording flowmeter installed in a large mainline and a paddle wheel flowmeter, respectively.

Figure 7–46 Typical in-line recording flowmeter

Figure 7–47 Paddle wheel electronic flowmeter installed in a large-diameter mainline

Figures 7–48 and 7–49 show a single jet flowmeter inserted into a lateral dripperline and connected to a RF transmitter in a cotton field irrigated by a MI system. The RF antenna transmits flow data to a remote control system, which manages the system's automation.

(3) Pressure gauges/transducers

The performance of MI systems depends on consistent control and knowledge of water pressure. Pressure gauges are inexpensive, readily available, but only provide visual pressure status when someone reads them. Pressure transducers are relatively expensive, require automation, but provide continuous data and safety factors and do not require visual reading. Regardless of how well the MI system is designed or how well the emitters are manufactured, operating pressures must remain at design specifications to maintain the desired performance and distribution uniformity. Manually monitoring pressures often or continuously with automation is important because changes in pressure can indicate a variety of problems. Depending on the location of the instrument, a pressure drop may indicate a leak, a component or line break, a blocked filter, or a malfunctioning pump. A pressure increase may indicate clogged filters, valves, main and submainlines, or partially clogged emitters. Minimum recommended locations for monitoring pressure gauges/transducers are shown in figure 7–19. They are recommended on the mainline, both before and after the filters, on the manifold in the field and downstream from pressure regulating valves to indicate the actual pressure supplied to the laterals. As with flow meters, readings from all pressure gauges should be recorded when the system is new and on a regular basis during operation. When automation is available, continuous monitoring of pressure transducers can be used to monitor the performance of MI systems, to shut down the system in case of problems or emergencies, and by using the rate of pressure change to determine emitter plugging.

(c) Main, submain, and manifolds

The main objective of a MI system is to provide an irrigation system such that when properly managed, each plant, vine, and/or tree will receive the same amount of water and nutrients, in sufficient quantity, at the proper time, and as economically as possible. For this goal to be realized, the system must deliver the needed pressurized amount of water to each emitter. Assuming that the headworks and other previously described components are performing properly, mains, submains, and manifolds must then deliver the water to the laterals and emitters.

Figure 7–48 Standard single jet flowmeter inserted into a lateral dripperline and connected to a RF transmitter through an aperture in the glass cover

Figure 7–49 Single jet flowmeter inserted into a lateral dripperline and connected to a RF transmitter

(1) Main and submainlines

The main and submainlines 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 submainlines is not affected by the pressure variation allowed for the subunit. Therefore, the pipe size should be selected based primarily on the economic trade-off between power costs and pipe installation costs. Design and installation of the main and submainlines should be in accordance with the National Handbook of Conservation Practices (U.S. Department of Agriculture Natural Resources Conservation Service).

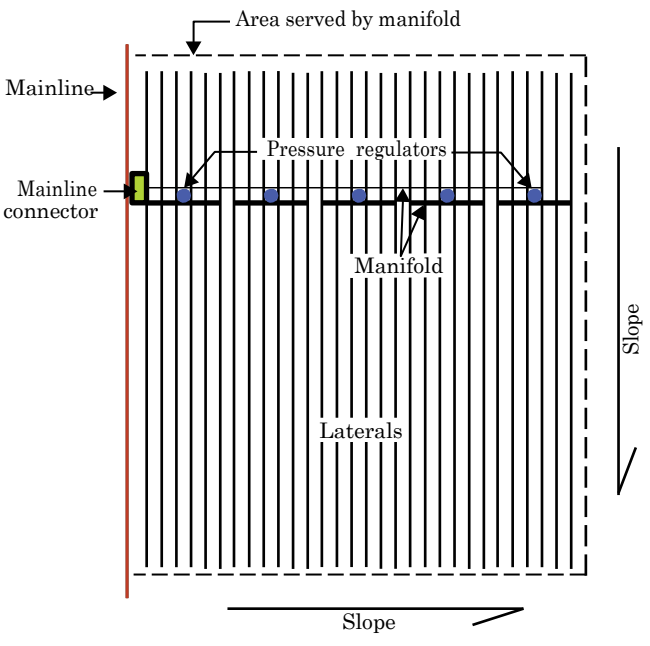
As with other irrigation pipelines, the flow velocity, check valves, air and vacuum relief valves, and pressure relief valves must be considered and incorporated as part of the system. A means of flushing and draining the pipelines also should be incorporated into the mainline and submain system. Factors to be considered in design and installation of pipelines include pipeline velocity, energy losses due to fittings, pressure ratings, surge pressures, temperature effects, thrust blocks and trenching and backfilling of pipelines, both in the operation and flushing mode.

(2) Manifold

The manifold, or header, connects the mainline to the laterals. It may be on the surface, but usually it is buried (fig. 7–50). The limit for manifold pressure loss depends on the topography, pressure loss in laterals, total pressure variation allowed for the emitter chosen, and flushing velocities. Once these limits have been established, standard calculations for hydraulic pipelines with multiple outlets may be used.

On flat terrain, the most economic location for the connection from submain or mainline to the 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.

Figure 7–50 Manifold layout showing inlet connection uphill from center and showing pressure regulated manifolds



Layflat flexible manifold on the surface and a buried rigid PVC manifold

(d) Laterals and emitters

(1) Laterals

In MI 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 polyethylene plastic tubing ranging from 3/8 to 1 inch in diameter (0.95–2.54 cm). 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. For tree crops, figures 7–51a through 7–51e show some typical layouts. As the trees mature, two laterals per row of trees may be needed (fig. 7–51b). 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. However, these last three layout methods (figs. 7–51c, d, and e) are less pressure efficient (too many elbows) and more difficult to maintain. In DI and SDI irrigated orchards, the preferred layouts are those shown in figures 7–51a and 7–51b.

For SDI systems on field, forage, and vegetable crops, the layout of the lateral lines should consider the emitter spacing, the depth of the laterals, the shape of the crop's root system, and the soil texture. Typical depth of burial is between 4 to 24 inches (0.1m–0.6m) and is very dependent on soil conditions, crop, and type of tape or tubing being used. Table 7–13 provides guidance for typical lateral spacings and burial depths for various crops.

Figure 7–52 shows a typical lateral connection to a buried manifold. This type of arrangement may be used for field as well as more permanent type of crops. Figure 7–53 shows installation method used for SDI drip tape. Figures 7–54 shows additional lateral layouts of both DI and SDI that might typically be used for crops other than trees.

(2) Emitters

In MI (drip, subsurface drip, low-pressure systems, or bubbler irrigation), emitters are used to dissipate pressure and discharge water at a constant rate and uniformly from one end of the field to the other. 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 path cross section or some means of flushing to reduce clogging, be pressure compensated and non-leaking when the system is shut off. Emitters should also be both inexpensive and compact. Two important numbers quantify how well a drip emitter performs: the coefficient of variation (CV) and the discharge exponent (x). Most drip system manufacturers publish CV and x values for all of their products or will provide them upon request. Several independent test labs also rate emitters and publish this information. These numbers are described in NEH623.0712.

Table 7–13 Typical lateral spacing and burial depth guidelines (after B.C. Trickle Irrigation Manual 1999)

Crop	Burial depth	Line spacing
Trees and grapes	>16 inches (0.4 m)	As per row spacing
Berries and vines	> 8 inches (0.2 m)	As per row spacing
Row crops—corn, cotton	≥ 12 inches (0.3 m)	24–80 inches (0.6–2.03 m)
Raised beds—single row Tomatoes, melons	2-4 inches (0.05–0.1 m)	One line 4–6 inches (0.1–0.15 m) from center of bed
Raised beds—double row onions, peppers, strawberries	2-4 inches (0.05–0.1 m)	One line down center of bed
Raised beds—double row > 30-inch (0.75 m) bed width	3-6 inches (0.075–0.15 m)	Two lines spaced half the bed width apart

Figure 7–51 Displays various lateral layouts used for a widely spaced permanent crop

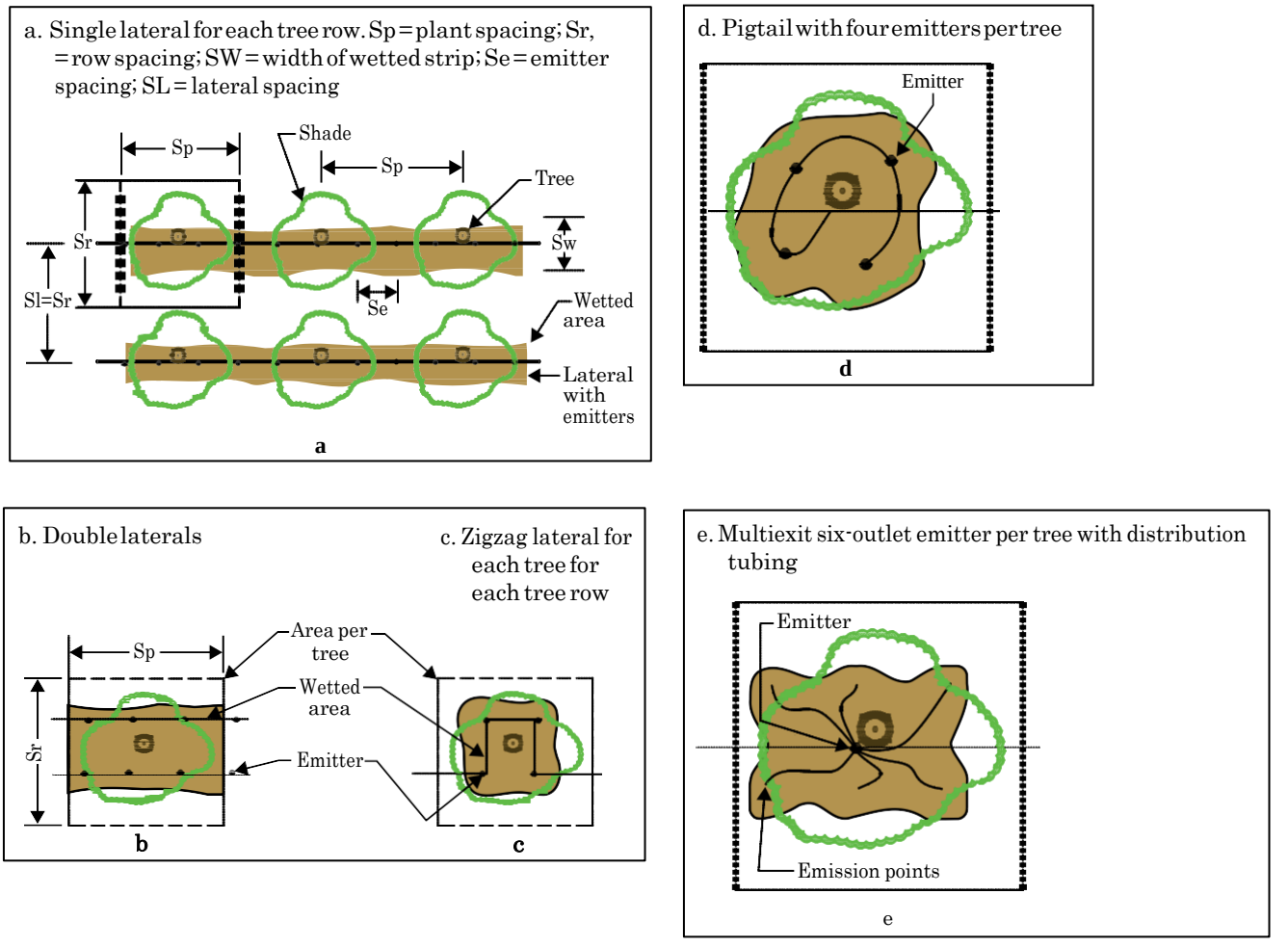
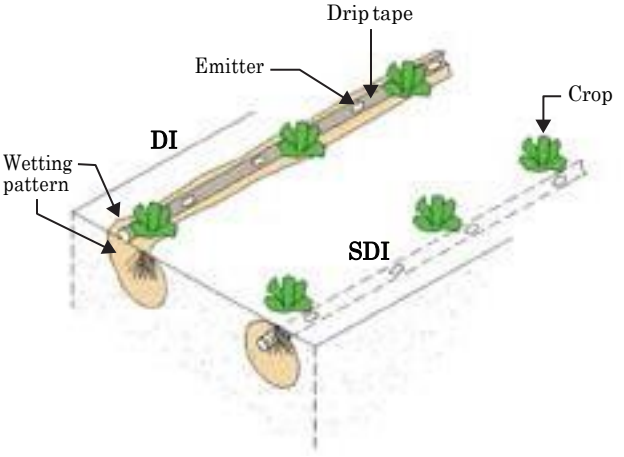


Figure 7–52 Permanent SDI manifold used for field and vegetable crops. Similar manifolds can be used for tree and vine crops using different lateral spacings

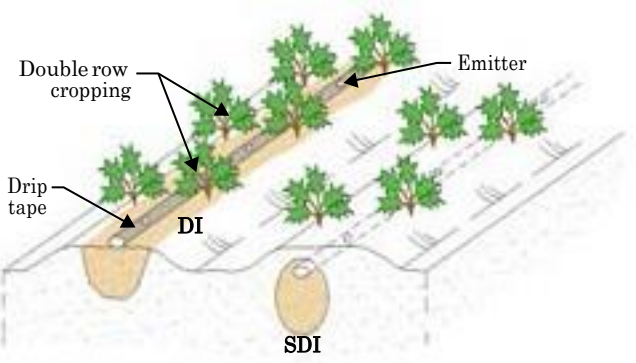
Figure 7–53 Installation of SDI drip tape on a corn field in Texas

Figure 7–54 Typical lateral layout

Typical lateral layout for single row crops both SD and SDI



Typical lateral layout for double row crop both SD and SDI



The point on or beneath the ground at which water is discharged from an emitter is called the emission point. MI with water discharged from emission points that are individually and widely spaced, usually more than 3 feet (0.914 m), is called point-source application.

Because of various conditions affecting microirrigation, 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 7–51 through 7–54 show construction and characteristics of emitters.

The emitter is the most important part of the MI system because it will dictate most of the specifications for the other components of the whole system. Numerous types of water application devices are manufactured and used. Howell et al. (1981) outlined 5 categories of emitters and gave 16 examples of emitters (after Solomon 1977):

- long-path emitters
- short-orifice emitters
- vortex emitters
- pressure compensating emitters
- porous pipe or tube emitters

In addition to these devices, MI systems also include microjets and microsprinklers. Emitter technology has improved considerably, and emitters are now often not only pressure compensated, but include nonleak, anti-siphon devices and mechanical and chemical root intrusion prevention. Many of the examples provided are no longer being used in the United States. Today, emission devices can be divided into six categories:

- heavy wall, semipermanent, discrete emitter drip lines
- thin-wall, discrete emitter dripper lines
- single chamber tapes
- button emitters
- microjet/microspray
- microsprinkler

Originally, a drip emitter consisted of an inlet, a flow channel, and an outlet. The first type of emitter was introduced in the mid-1960s and consisted of a microtube wound around a delivery pipe with the length of the microtube determining the discharge rate of the device for a given pressure. An integrated drip emitter consisting of an inlet, a flow channel, and an outlet all included within the same unit was introduced in the 1970s. The inlet allowed water into the flow channel from the drip lateral. The flow channel was a narrow path, designed to slow down the laminar flow of water and reduce the water pressure by friction loss. The emitter outlet was a small opening at the end of the flow channel through which the water dripped into the soil. The emitter was then inserted between two lengths of polyethylene tube. Figure 7–55 shows a schematic of one of these widely used, early-type laminar flow emitters and shows one of these emitters being used to irrigate.

Heavy wall, semipermanent, discrete emitter drip lines—In the 1980s, pressure compensation was introduced to discrete emitter drip lines by adding a pressure-sensitive membrane. Figure 7–56 shows a pressure compensated (PC) emitter that has been used extensively for surface and subsurface drip. The pressure compensation allowed the extension of lateral length and the installation in undulating terrain. However, these emitters drained at low points along the laterals, which was detrimental to application uniformity under high-frequency irrigation scheduling. The next advance came in the late 1990s when the nonleak, antisiphon concept (CNL) emitter was introduced. Figure 7–57 shows a PC–CNL emitter. This emitter is extremely advantageous for preventing drainage at low points on undulating terrain, for preventing soil ingestion into SDI systems when the system is switched off, and for high-frequency irrigation scheduling. The PC–CNL will not discharge water when the pressure drops to about 13 feet (4.0 m), This emitter discharges water at a predictable and consistent rate, emits water at nearly the same rate for a range of supply pressures, resists plugging, prevents soil ingestion in SDI systems, and reduces drainage at low points when the system is switched off.

Figure 7–55 Schematic of an early (1967–70) in-line pressure laminar flow emitter (*courtesy Netafim USA*)

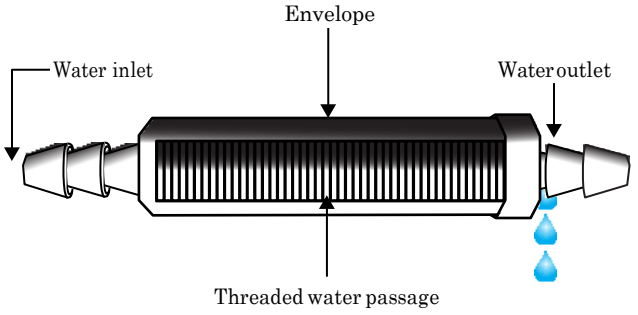


Figure 7–56 Schematic of an in-line, pressure compensated emitter (1980s) (*courtesy Netafim USA*)

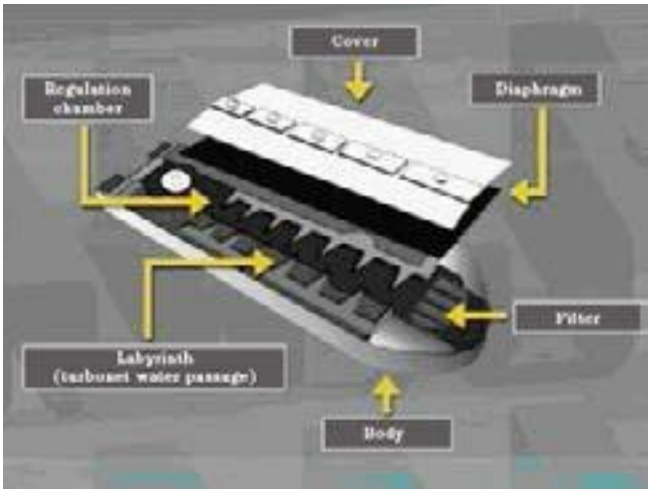
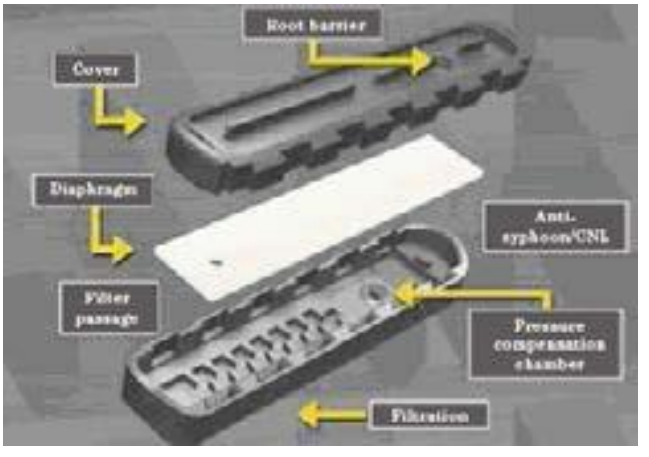


Figure 7–57 Schematic of an in-line, pressure compensated emitter, incorporating the nonleak anti-siphon concept (1990s) (*courtesy Netafim USA*)



Thinwall dripper lines—Thinwall dripper lines provide a less costly, short-term alternative type of drip line than heavy wall, semipermanent, discrete, emitter drip lines. They do not have the long life expectancy of the heavy wall semipermanent drip systems, but offer the integrity of a discrete emitter line. They are often used for field and vegetable crops. Figure 7–58 is a schematic of a nonpressure compensated emitter for thinwall dripper line (late 1980s).

Drip tapes—Drip tape is another short-term alternative drip line to heavy wall, semipermanent, discrete emitter drip lines. In the tape, the emitting device consists of an inlet, a flow channel, and an outlet. The inlet allows water into the flow channel from the main chamber of the drip tape. The flow channel is a narrow path with a complex shape designed to slow down the flow of water and create turbulence, which prevents contaminants from settling. The emitting outlet is a small opening at the end of the flow channel through which the water drips into the soil (fig. 7–59). A well-engineered drip tape emits water at a predictable and nearly consistent rate, but it is more susceptible to changes in supply pressures and based on design, it may resist plugging.

Like other drip systems, drip tapes can be affected by plugging and can become nonuniform to a point where they become completely debilitated in the midst of a growing season. Tapes can be more prone to plugging than heavy wall, semipermanent, discrete, emitter drip lines because they are collapsible.

Button emitters—Button emitters are used mostly for landscape and greenhouse applications. However, one of the advantages of button emitters is the ability to increase the number of emitters as the demand for water increases with maturing tree or vine crops. Figure 7–60 is a schematic of a pressure compensated, turbulent flow button emitter with barbed outlets and a button emitter used to irrigate a fig tree.

Microjet/microspray—Microjets/microsprays systems discharge water in a small uniform spray of water to cover an area of 10 to 100 square feet (0.96 to 9.3 m^2) with water application rates ranging from 5 to 60 gallons per hour (19 to 227 Lph). Sprayers should have a low water trajectory and a single large flow cross section and should apply the water evenly. Microjets/microsprays systems are typically used with tree crop applications where wider wetting patterns or larger flow rates are desirable. They may also be used in unfavorable soil conditions or poor water quality. Microjets/microsprays systems may be selected instead of microsprinkler to avoid moving parts that may jam or clog. The wheel spoke application pattern also minimizes saturated soil conditions and improves rootzone

Figure 7–58 Schematic of a nonpressure compensated emitter for thinwall line (1980s) (*courtesy Netafim USA*)

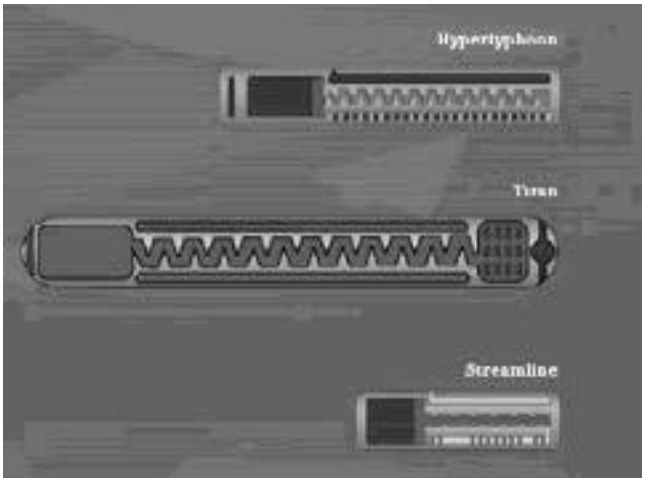


Figure 7–59 Picture of a widely used single chamber drip tape irrigating strawberries

aeration. Figure 7–61 shows a single lateral microjet system used on young citrus trees.

Microsprinkler—Microsprinklers systems discharge water in a small uniform jet of water to cover a 360-degree circular pattern with a covered area of 100 to 200 square feet (9.3 to 19.5 m^2) and water application rates ranging from 10 to 63 gallons per hour (35 to 240 Lph). Microsprinklers should have a low water trajectory and a single large-flow cross section and should apply the water evenly. Microsprinkler systems are typically used with tree crop applications where frost protection is needed and wider wetting patterns or larger flow rates are desirable in unfavorable soil conditions or water quality. Frost protection results from the generation of heat of fusion as water turns to ice (from liquid to solid) and from the cooling of water. The sprinklers can be located under the trees, over the trees, or at a targeted location. Figure 7–62 shows a microsprinkler system in an almond orchard.

Figure 7–60 Schematic of a pressure compensated, turbulent flow button emitter *(courtesy Netafim USA)*

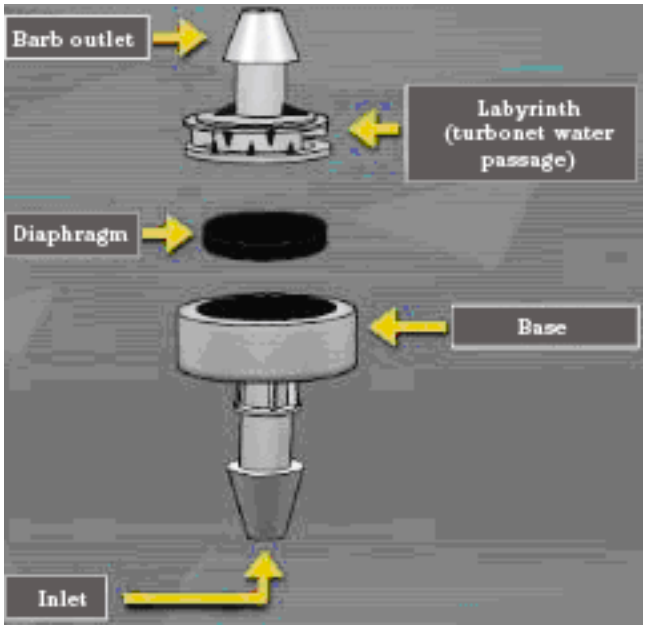


Figure 7–61 A single lateral microjet system in a young citrus trees

Figure 7–62 A microsprinkler system in an almond orchard

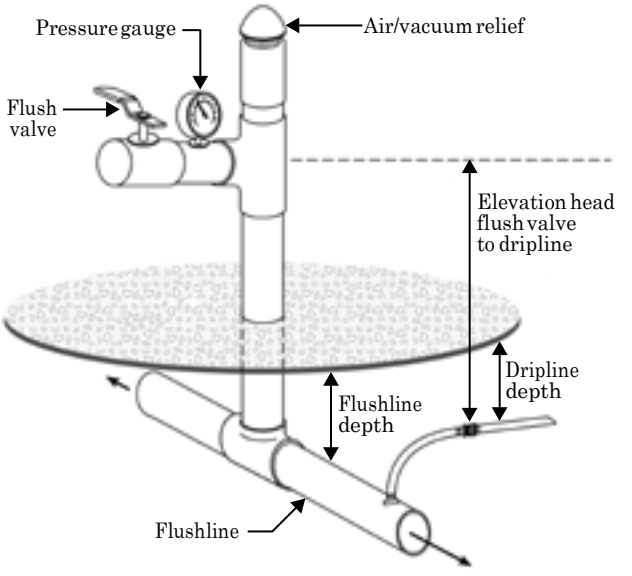
(d) Flush system

The flushing system is comprised of most of the components described in previous sections and, in addition, typically includes flush valves and flush manifolds at the downstream end of the laterals (fig. 7–63). A means of flushing and draining the pipelines is also incorporated into the main, submain, and manifolds. A flushing system also requires a drainage sink to remove the flush water from the site.

Flushing of a MI system is required to remove particles and organisms that pass through the filtration system and accumulate in the pipelines, manifolds, and laterals. Flushing involves pushing water through the system at a sufficient velocity to resuspend the sediment that has accumulated and allowing the flush water to exit the system.

Always consider the flushing requirements during the design phase because pumps, mains, and submains must be able to provide and maintain the flow velocity needed for flushing. Although adequate filtration can reduce the frequency of flushing, flushing should be done at least annually. In some systems, it may be necessary to flush more often. Each MI system should be monitored for clogging to avoid a complete shutdown of the system. Clogging of emitters occurs gradually, results in a progressive deterioration of system performance, and negates some of the advantages of microirrigation.

Figure 7–63 Branched flushing manifold detail (*courtesy F.R. Lamm and Kansas State University*)



623.0709 Operations and maintenance

(a) Operation

The procedures used for operating and maintaining MI system components are critical factors involved in the success or failure of any MI system. The management objectives of MI are:

- apply a small volume of water as frequently as needed to maintain a portion of the rootzone under nearly constant soil water to prevent plant water stress from occurring
- manage it as desired to achieve a predefined plant growth and quality objective
- achieve both previous objective simultaneously

Assuming proper system design, installation, and management, operating a MI system will maintain some of the soil surface dry, eliminate runoff, and minimize deep percolation of water below the rootzone and leaching of soluble nutrients (such as nitrate-N) to the ground water. A general operating procedure for a MI system involves the following steps for the owner-operator:

Step 1: Acquiring complete components information and instructions from the designer and dealer and fully understanding the operating instructions.

Step 2: Frequently determining when and how long to irrigate. For an automated system, this can be done daily with a weather station or an evaporation pan with or without soil moisture feedback (figs. 7–22, 7–23, and accompanying text). For a manual system, determining when and how long to irrigate should be done at a minimum of once a week and irrigation should be applied daily at a seventh of the weekly demand.

Step 3: Checking the water meter measurements and recording these figures either manually or automatically. Mechanical water meters should be recalibrated yearly.

Step 4: Accurately setting the control system and understanding its functions.

Step 5: Operating the head valve to begin irrigation.

Step 6: Checking the system components for proper operation, beginning with pressure and flow measurements at the header.

Step 7: Checking the discharge rate of emitters, at least on a random basis.

Step 8: Measuring the pH and ECw of the water and setting the chemical and fertilizer injection equipment according to the water quality and the crop nutrient demand. Fertigation and chemigation are described in details in NEH623.0706 and 623.0707, respectively.

Figure 7–64 is a flowchart describing the sequence of major events involved in the operation of either a manually or automated MI system. The coarser the soil texture, the more frequent the irrigation system will need to be turned on and, depending on the crop water requirement and the crop sensitivity to water stress, the number of irrigation could vary from two or three per week to several daily irrigations. Because of this, it is time and labor advantageous to use an automated control rather than manual irrigation control. Note that there are some interactions between the operational flowchart (fig. 7–64) and the maintenance flowchart (fig. 7–65). These interactions are represented by circle and specific item numbers for each figure.

(b) Maintenance

Reliable performance of a MI system depends on preventive maintenance that includes proper filtration, pipe flushing, and field checks of mechanical and electrical devices. The various methods of cleaning filters were described 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, installation, or repairs, the irrigation system must be flushed systematically, beginning with the headworks, then, the mainline and proceeding to the submains, manifolds, and laterals. The mainlines 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 increases the flushing velocity of water. The manifolds should be flushed with all the lateral riser

Figure 7–64 Operational flowchart for managing irrigation, either manually or automatically with a computerized irrigation controller, as described in figure 7–22

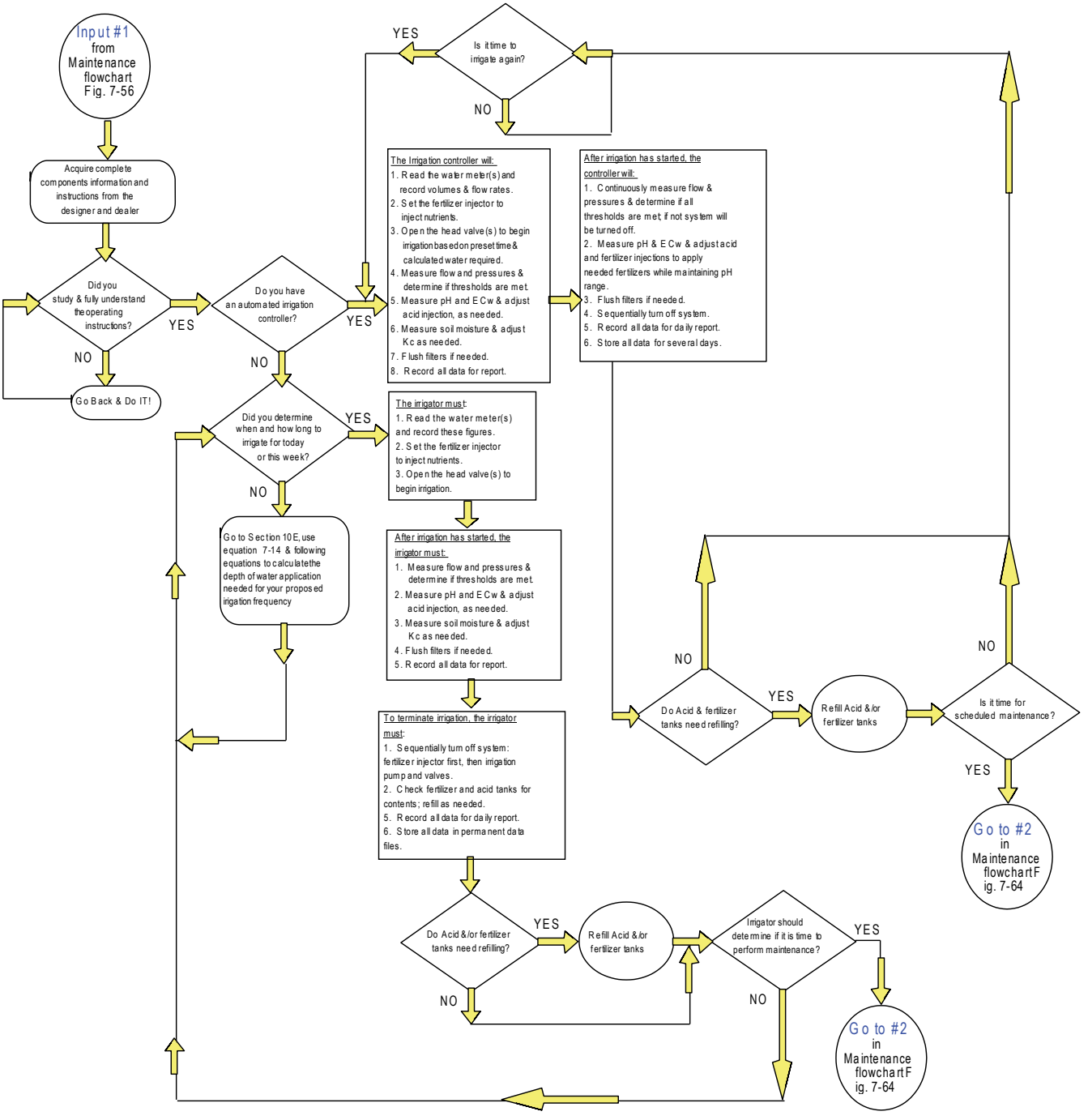
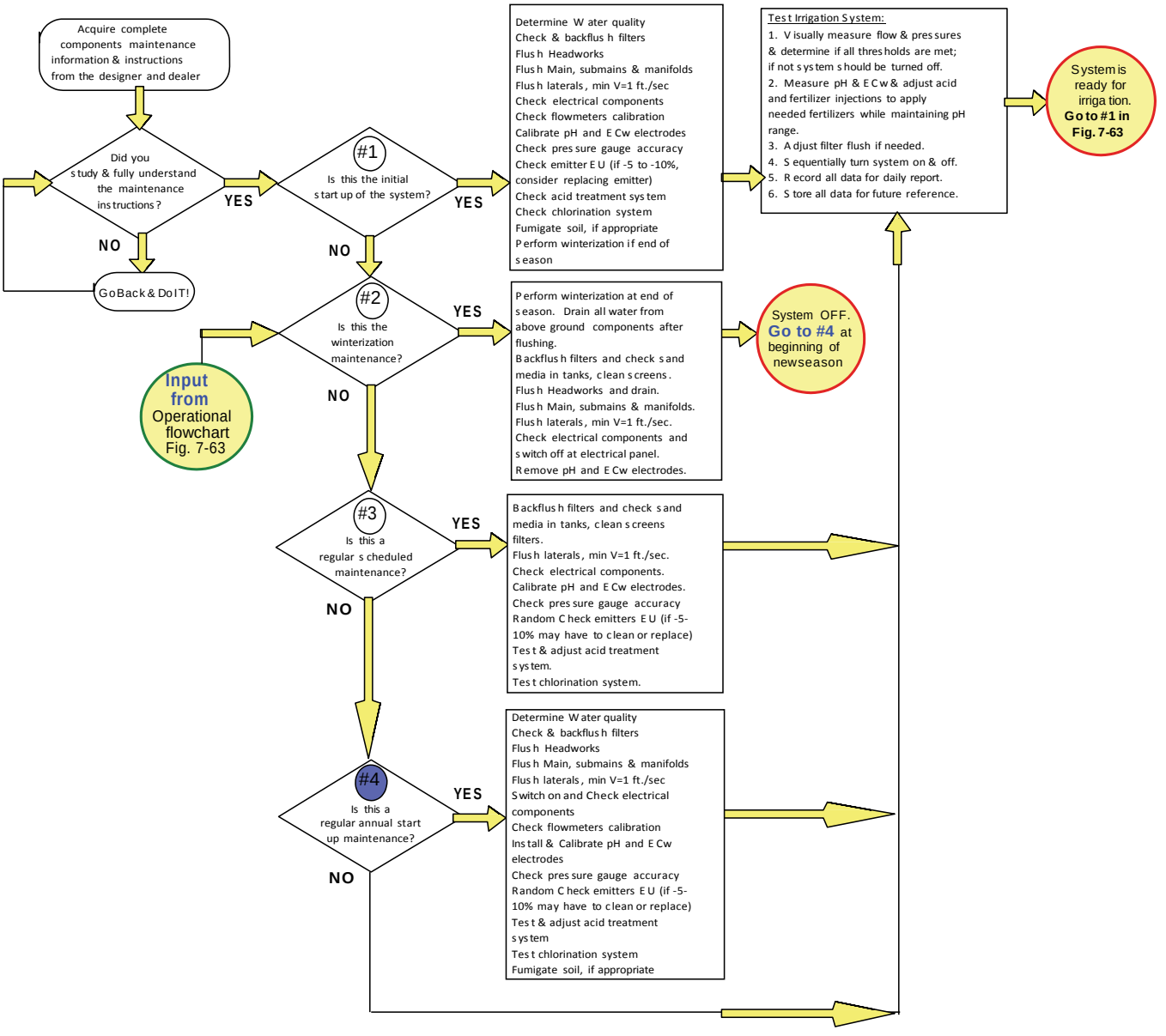


Figure 7–65 Maintenance flow chart for either a manual or an automated system



valves turned off. Finally, the lateral hoses should be connected and flushed for about an hour (depending on the lateral length) on each operating station. Fine sand, silt, and clay tend to settle in the low-velocity sections of the system, at the ends of manifolds and laterals, and at low elevation points. Emitters receiving high concentrations of these fine contaminants are susceptible to clogging; therefore, periodic flushing is a recommended part of an adequate maintenance program. Annual flushing is sufficient for many systems, but for some systems, water and emitter combinations require almost daily flushing to control clogging.

For any installation where the drip laterals are installed below the soil surface, such as in SDI and LPS systems, there is a potential for soil ingestion into the laterals when the system is turned off and adequate vacuum breaker valves are not strategically located. In these cases, daily flushing may be required. If frequent flushing is required, automatic and semiautomatic flushing valves are recommended at the ends of the laterals. A minimum water velocity of about 1.0 foot per second (0.3 m/s) is required to flush fine particles from lateral tubing. For 0.5-inch (12.7 mm)-diameter tubing, this is equivalent to 1.0 gallons per minute (3.785 l/min).

Systematic checking is required to spot malfunctioning emitters or to use accurate flow and pressure measurements and analyze their rates of change over time. 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 between 5 to 10 percent below the design uniformity or when the average emitter discharge (qa) times EU/100 is insufficient to satisfy the plants' requirements for water.

The cleaning required depends on the filtration, overall system design, emitter design characteristics, and the water quality (table 7–2). Some emitters can be disassembled and cleaned manually. Others can be flushed to get rid of loose deposits. Carbonate and bicarbonate concentration in excess of 150 parts per million (mg/kg) will usually precipitate when the pH of the irrigation water exceeds 7.5. Injecting 0.5 to l percent sulfuric acid solution at manifold or lateral inlets can dissolve carbonate and bicarbonate precipitates. With this acid treatment, a minimum contact time of 5 to 15 minutes in the emitters will normally suffice, provided that the emitter flow path is not fully clogged. Sulfuric acid should also be used for iron precipitates. When the water quality factors exceed the levels recommended in table 7–2, then follow the recommendations provided in NEH623.0706.

Acid treatment may not always be practical or 100 percent effective and, obviously, may be ineffective for completely clogged emitters. Air pressure of 70 to 140 psi (5 to 10 atm) applied at lateral inlets can remove jellylike deposits from long-tube emitters. However, the emitters and connections to the lateral hose must be very strong to withstand this high 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 practically impossible for most emitters.

Pipeline, valves, and electrical pumps require little maintenance. Normal precautions should be taken for drainage at shutdown time and for filling at the beginning of the irrigation season. Before startup and during the irrigation season, components should be lubricated according to the manufacturer's recommendations. For gasoline or diesel driven pumps, engine maintenance and repairs should be performed during the off-season.

Figure 7–65 is a flowchart describing the sequence of major events involved in the maintenance of either a manually or automated MI system. Maintenance schedules are divided into four types:

- initial system maintenance that should occur after the installation and before any irrigation starts
- system winterization that should occur before shut down for the winter to clean and drain the system and avoid frost damage
- in-season regular scheduled maintenance to ensure accuracy of the water delivering system, usually during the peak ET period

- regular annual start-up maintenance and cleanup to ensure adequate functioning of the system, following several inactive months

Note that there are some interactions between the operational flowchart (fig. 7–64) and the maintenance flowchart (fig. 7–65). Circles represent these interactions with specific item numbers for each figure.

623.0710 Soil-plant-water relations

MI systems replace the soil water storage concept utilized by conventional irrigation systems. A small volume of soil is maintained at a constant soil matric potential due to frequent moisture replacement. The advantage of a MI system is that it can accurately replace water lost by the evapotranspiration and drainage. This process is referred to as "high-frequency irrigation (HFI)." Systems operated in this mode can help to prevent plant water stress from occurring or to manage plant water stress as desired to achieve a predefined plant growth and quality objective. Managing a HFI system requires knowledge and understanding of the wetted soil volume, wetting pattern, and the dynamics of water movement in soil.

(a) How water movement in the soil works

Water moves in soil under mass flow (liquid state) and/or slowly by diffusion (vapor state). Forces controlling the movement of water are mostly due to the capillary nature of soil (capillary force field) that acts equally in all directions and the gravitational force field that is always constant and downward. The capillary force dominates when the soil is dry, but decreases quickly as the soil wets.

Figure 7–66 shows the effect of soil texture on soil water content. The zone used for high-frequency irrigation has a very narrow range in the coarse, sandy soil, increasing slightly as the soil texture increases towards the clay soil. Figure 7–67 shows typical patterns of soil water distribution from a subsurface point source in a homogeneous soil, as affected by irrigation duration and soil textures. Figure 7–68 shows patterns of soil water distribution from a subsurface point source in a stratified soil, as affected by irrigation duration and soil textures. As the water-holding capacity of soil decreases with soil coarseness, the duration of the irrigation pulse should be reduced to minimize deep percolation below the rootzone and/or upward channeling of water to the soil surface, especially when the soil is stratified (fig. 7–68). Furthermore, because DI and SDI systems concentrate the emission of water to a point source, the soil saturation under the

Figure 7–66 Relative soil water content as affected by soil texture

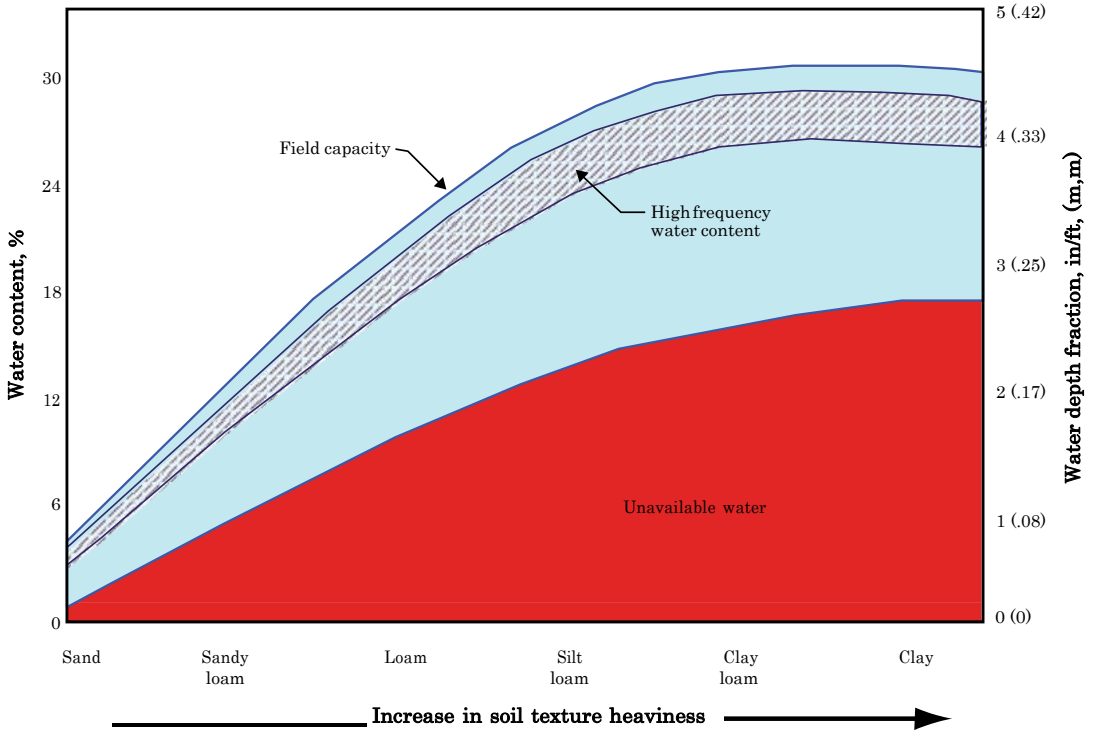


Figure 7–67 Idealized patterns of soil water distribution from a subsurface point source in a homogeneous soil, as affected by irrigation duration and soil textures

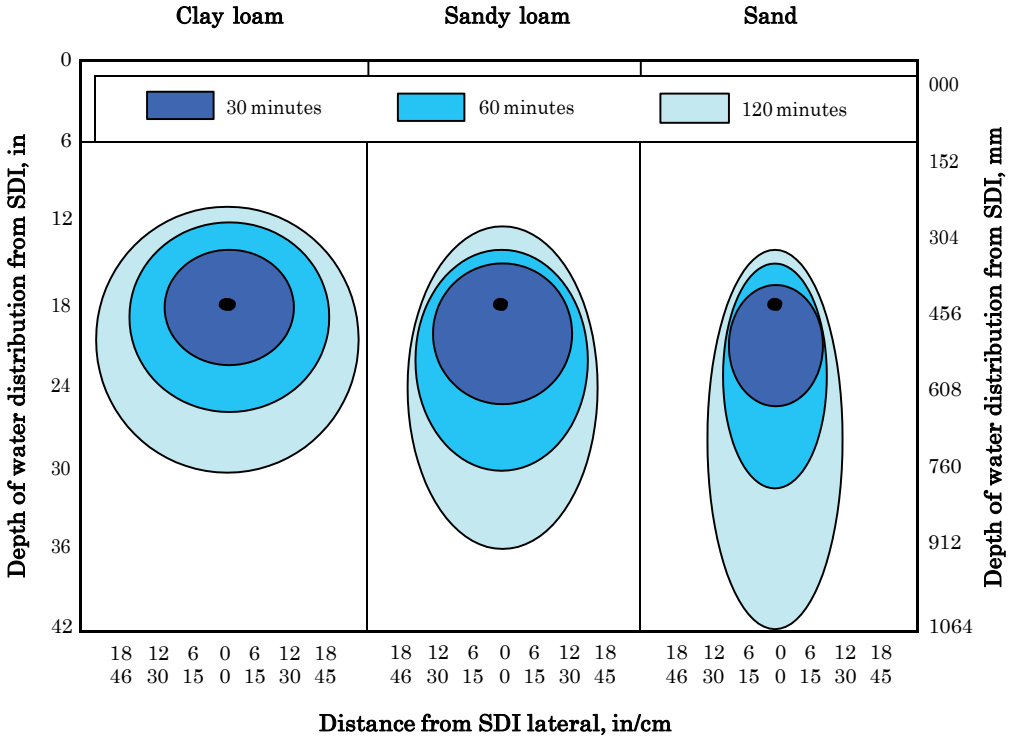
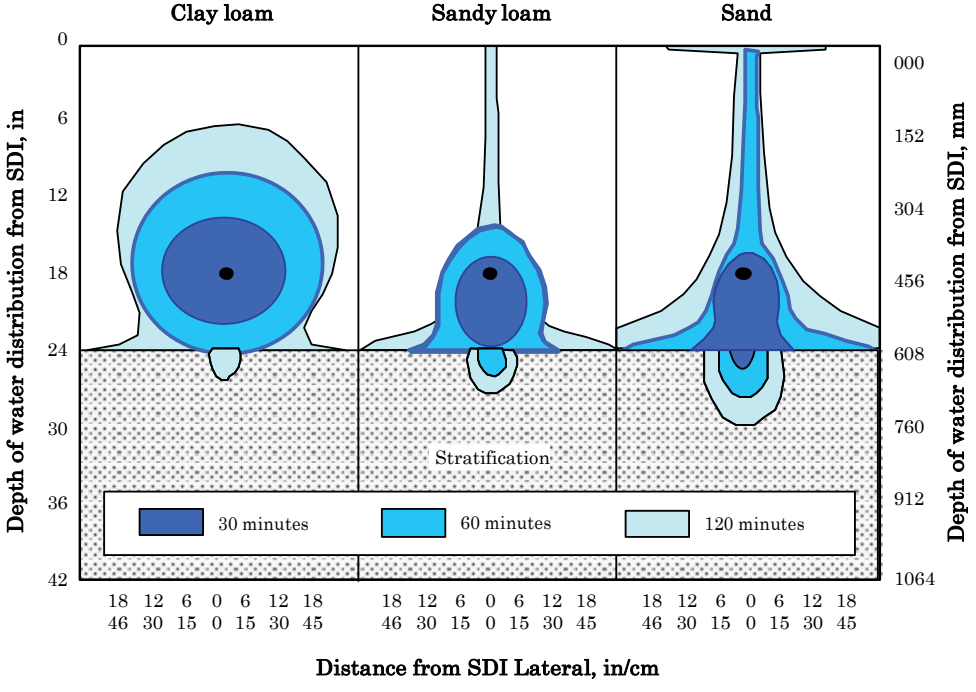


Figure 7–68 Idealized patterns of soil water distribution from a subsurface point source in a stratified soil, as affected by irrigation duration and soil textures



emission point occurs very rapidly and has the tendency to maximize drainage unless the emitter discharge rate is slower than the soil hydraulic conductivity.

The basic HFI objective consists of irrigating in short pulses with an emitter discharge rate lower than the soil infiltration rate (surface MI) or unsaturated K for SDI systems, so that the water movement is controlled mostly by the capillary force field rather than by the gravitational force field. The timing between irrigation events also allows additional distribution of water under capillary action. Therefore, successfully controlling water application with DI and SDI will be more demanding than with conventional irrigation methods.

(b) Potential of high-frequency irrigation scheduling

Under conventional irrigation scheduling, water is applied over a large soil surface area to replace several days of evapotranspiration. Since daily evapotranspiration rates are extremely variable and unpredictable, the probability of applying the correct amount of water for the next cycle is low. On the other hand, the high-frequency system has the potential to be adjusted for the change in daily evapotranspiration demand, measured, as often as hourly; hence, the probability of applying the correct amount of water is higher.

(c) Soil wetting patterns

The wetted soil volume (V_w) generated by a DI system when water is applied under HFI irrigation scheduling will develop along a horizontal plane starting at the soil surface for a surface system or at various depths below the soil surface for a SDI system. Because of variations in infiltration rate, texture, structure, slope, and horizontal stratification of soil, a mathematical relationship to determine V_w will not be accurate unless the variables are well defined. A reliable but time-consuming way to determine V_w is to conduct field tests in which test emitters are operated at a few representative sites in a field and the wetting patterns are determined. The flow rate and volume of water applied in the test should be similar to the design values expected for the system under consideration. This practice is difficult to perform with SDI systems because the soil has to be disturbed. This equipment is recommended to perform a field test:

- 20- to 30-gallon (76 to 114 L) pressurized container, equipped with a pressure gauge
- stand for the container, a trailer or the bed of a pick up truck
- 10-foot (3.05 m) piece of 1/4- or 3/8-inch- (6.4 or 9.5 mm) diameter tubing to the bottom of the container
- 120-mesh screen filter to prevent clogging the emitter
- turbulent flow emitter with a discharge rate equal to the expected system design flow rate, at a given design pressure
- 0.0265-gallon (100 ml) graduated cylinder
- watch with a second hand
- shovel
- soil auger

The test is performed as follows:

Step 1: Place the container on the stand and calibrate the test emitter by measuring its discharge rate at a given pressure. If this is not a pressure compensating (PC) emitter, then the test should be repeated at a range of pressures.

Step 2: Position the test emitter on the smoothed dry soil.

Step 3: Fill the pressurized container with the amount of water required to provide the expected design daily flow for an emitter.

Step 4: Release the daily flow requirement through the test emitter by applying water pulses at the expected management frequency. The down time between pulses should be equal to the duration of the pulse. If the soil is very dry, wait 24 hours before checking the wetting pattern.

Step 5: Dig a trench 36 inches (0.914 m) deep through the test emitter location.

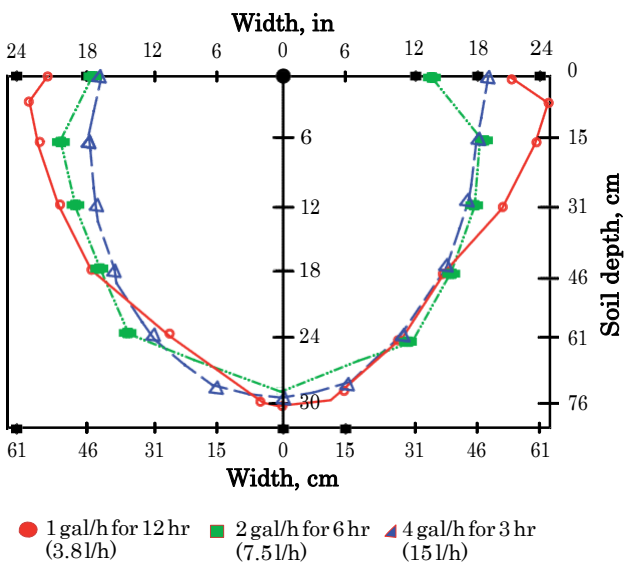
Step 6: Measure the width and depth of wetting at 6-inch (0/152 m) intervals from the test emitter.

Step 7: Plot the cross section, and compute the wetted volume (assume symmetry).

Figure 7–69 shows the measured wetting patterns for 12 gallons of water applied to a dry sandy-clay soil at rates of 1, 2, and 4 gallons per hour. The sandy clay-textured desert soil was dry before the test. Note that even though the system was not operated as HFI, the wetting patterns are not similar for the three rates with equal volumes of water applied. Near the soil surface, the 1 gallon per hour emitter produced a 33 percent wider wetted volume than the emitters with higher flow rates. The 4 gallons per hour emitter did not cause ponding, but may have approached the value of the saturated hydraulic conductivity. Because of its relatively low discharge rate, the 1 gallon per hour emitter maintained the unsaturated water condition for a longer period of time and promoted greater horizontal water movement. With HFI wettings, the area wetted would probably have been larger, even for the emitter with a higher discharge rate. Today, most of the emitters are available with discharge rates from 0.2 to 1.0 gallons per hour.

Figure 7–70 shows the relationship between the maximum horizontal and vertical movement in a uniform sandy soil for emitter discharge rates of 1, 2, and 4 gallons per hour. The data points in figure 7–70 demonstrate that, in uniform soils, the volume of soil wetted depends on the application rate and the amount of water applied, at least until the drainage component takes over (irrigation length exceeding the ability of the soil to move water by capillary action). The 1:1 line in figure 7–70 also shows that for the 1 and 2 gallons per hour emitters, the ratio of the vertical to the horizontal component is always less than one implying that water is moving horizontally more than vertically; however, in the case of the 4 gallons per hour emitter, the first three measurements are the only time when the ratio is less than one, implying that for the other three points, the water is draining. Thus, to avoid water moving past the rootzone, short and frequent applications should be recommended to minimize deep percolation losses, recognizing that in the process the emitter may wet a smaller volume of soil, much of it being dependent on the soil texture and the infiltration rate of the soil. The other observation is that the wetting pattern for the 1 and 2 gallons per hour emitter is nearly hemispherical, as shown in fig. 7–69.

Figure 7–69 Soil wetted patterns for water volumes of 12 gallons each, applied at three rates to a dry sandy soil



When this is compared to a subsurface drip system several differences become readily apparent. Ben-Asher and Phene (1993) and Phene and Phene (1987) have simulated soil wetting patterns and have shown that with an homogeneous soil and for a given discharge rate of water:

- The spherical volume of a moist clay loam soil is approximately 46 percent larger for the SDI system than the hemispherical volume wetted with a similar DI system.
- The corresponding wetted surface area available for root uptake is 62 percent larger in the SDI system than in the DI system (excluding the soil surface in the surface drip pattern.
- The wetted soil radius is 10 percent shorter in the SDI than in the DI system (fig. 7–71).

The implications of figure 7–71 are that under similar irrigation conditions:

- The wetted soil volume in the SDI system will be at a lower water content than in the DI system and the leaching potential will be lowered.
- The surface area of soil available for root uptake of water and nutrients will be increased in the SDI system.
- The shorter wetted radius in the SDI system will allow closer emitter spacing than in the DI system, resulting in potentially improved wetted uniformity.

Figure 7–70 Relationship between vertical and horizontal water movement in a dry sandy soil

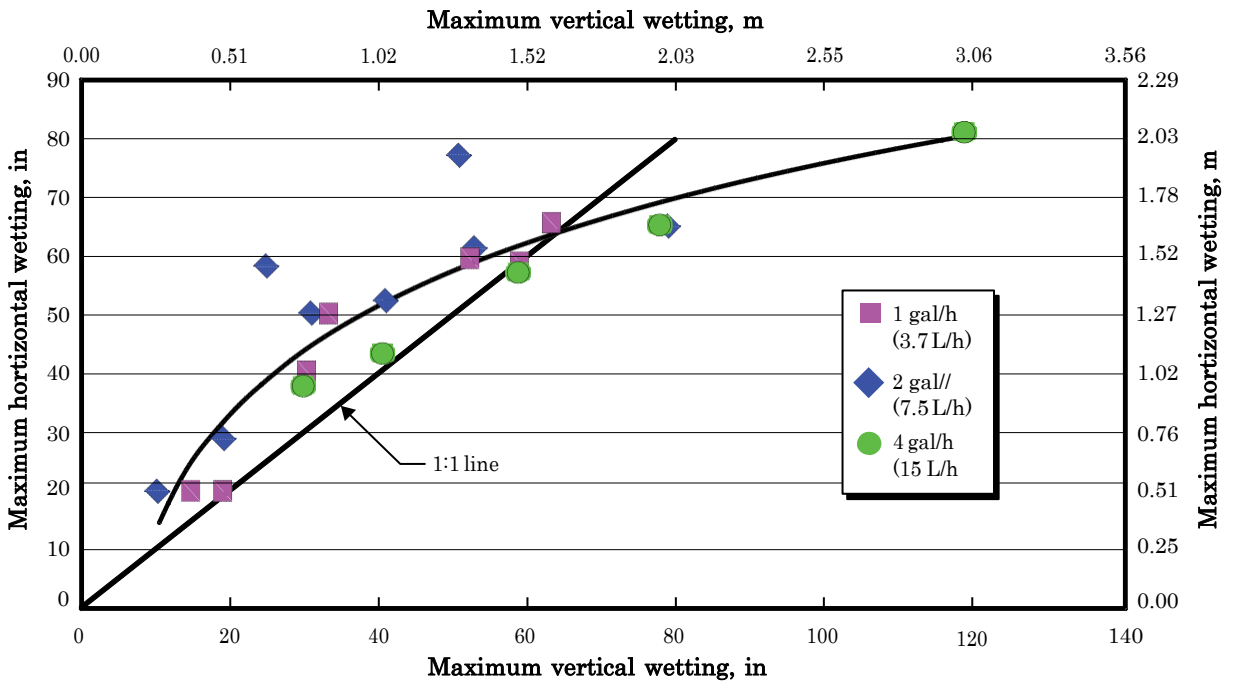


Figure 7–71 Simulated soil wetted patterns created in a dry Panoche clay loam soil

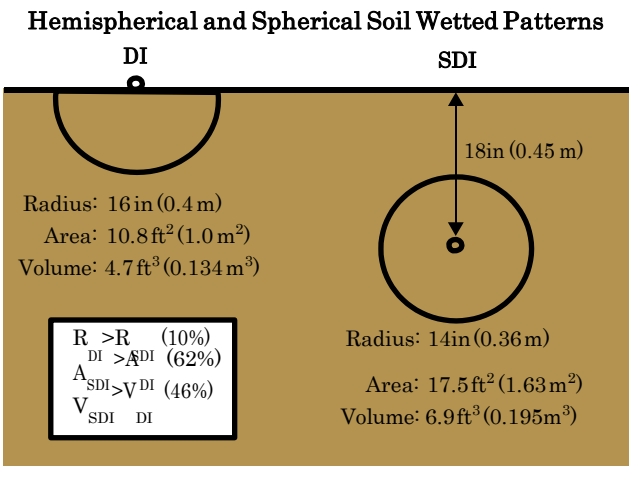


Figure 7–72 illustrates soil wetted patterns generated in a Panoche clay loam soil planted to acala cotton by a DI (top) and a SDI (bottom) system with discharge rate of 2 L/h under steady state conditions of high-frequency, 1-hour irrigation period (Phene and Phene 1987).

Spray emitters wet a relatively large surface 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 soil volume. Spray emitters, on the other hand, are subject to evaporation, and they increase humidity and may promote diseases such as Phytophtora and Alternaria.

Figure 7–73 compares wetting patterns and areas wetted under drip and spray emitters. Water moves out laterally from the wetted surface area under a spray emitter, similarly to the movement observed for the point source emitter. Most soils have layers of various densities, textures, or both. Generally, soil stratification impedes the downward movement of water across the interface of two soil strata, regardless of their relative texture or density (for different reasons). Figure 7–68 shows the expected wetting patterns in a stratified soil. However, assuming large wetting pattern values without performing field tests (as described earlier) is risky. With many differences in the texture and density of the soil layers, the wetting pattern may be twice as large as the values given for a layered soil in table 7–14, but this can only be determined by actual field checks. Table 7–14 should be used only for estimation. Values of A_w greater than those given for uniform texture and low-density conditions should be used with caution until they are checked in the field.

Table 7–14 gives estimates of A_w at a depth of about 6 to 12 inches (0.15 to 0.30 m) in soils of various textures. The table values are based on a common emitter flow rate of 1.0 gallons per hour (3.785 L/h) 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. However, the depth of the wetting pattern is of greater importance than the wetted surface area because of the various variables that impede the infiltration of water in soil and the majority of the root system that is usually located deeper than 6 to 12 inches (0.15 to 0.30 m).

Figure 7–72 Soil wetted patterns generated in a Panoche clay loam soil planted to acala cotton

Figure 7–73 Idealized wetting patterns in a homogeneous, fine, sandy soil under a drip and a spray emitter

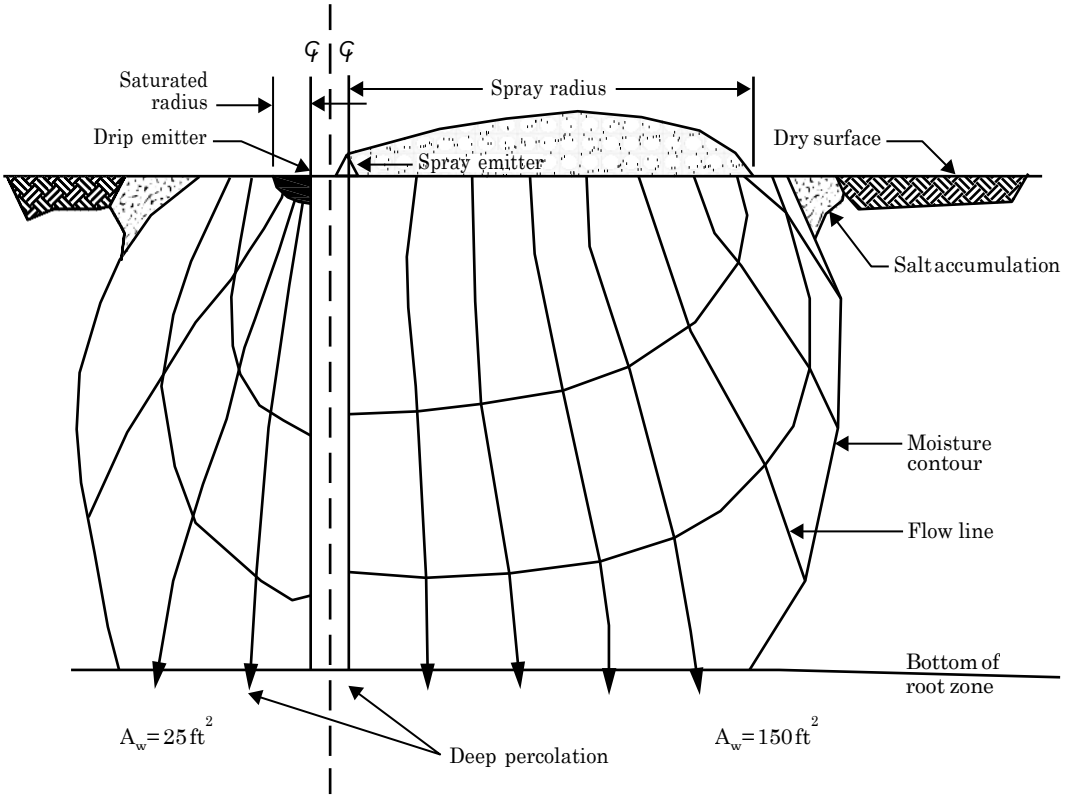


Table 7–14 Estimates of area (A_w) [1] wetted in various soils

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)(cm²)		$S'_e \times S_w = A_w$ (ft²)(cm²)		$S'_e \times S_w = A_w$ (ft²)(cm²)	
Depth	2.5 ft	76 cm	2.5 ft	76 cm	2.5 ft	76 cm
Coarse	1.2×1.5 =1.8	37×46=1,702	2.0×2.5=5.0	61×276=4,645	2.8×3.5=9.8	85×107=9104
Medium	2.4×3.0=7.2	73×91=6643	3.2×4.0=12.8	98×122=11,892	4.0×5.0=20.0	122×152=18,581
Fine	2.8×3.5=9.8	85×107=9,104	4.0×5.0=20.0	122×152=18,581	4.8×6.0=28.8	146×183=26,756
Depth	5 ft	152 cm	5 ft	152 cm	5 ft	152 cm
Coarse	2.0×2.5=5.0	61×76=4,695	3.6×4.5=16.2	110×137=15,050	4.8×6.0=28.8	146×183=26,756
Medium	3.2×4.0=12.8	98×122=11,892	5.6×7.2=39.2	171×219=37,459	7.2×9.0=64.8	219×274=60,201
Fine	4.0×5.0=20.0	122×152=18,591	5.2×6.2=33.8	158×198=31,401	6.4×8.0=51.2	195×244=47,566

1 Based on an emitter flow rate of 1 gallon per hour (3.785 L), 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.

(d) Percent area wetted

The percent area wetted (P_w) is the average horizontal area wetted in the top 6 to 12 inches (0.15 to 0.30 m) of the rootzone as a percentage of the total crop area. For a DI 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 7–8.

$$P_w = \frac{S_e S_w}{S_p S_r} \times 100 \qquad \text{(eq. 7–8)}$$

where:
P_w = percent area wetter (%)
S_e = spacing between emitters on a lateral, ft (m)
S_w = width of the strip that would be wetted by emitters on a lateral at a spacing of S_e' or closer, ft (m)
S_p = plant spacing in the row, ft (m)
S_r = plant row spacing, ft (m)

On sloping fields, the wetting pattern is distorted along 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 vertical direction of the pattern and the placement of emission points.

For DI systems with straight laterals of single drip emitters where S_e is greater than the optimum emitter spacing (S_e') (80% of the wetted diameter, feet), S_e in equation 7–8 must be replaced by S_e'. For DI systems with double laterals or zigzag, pigtail, or multiexit layout, the P_w can be computed by equation 7–9.

$$P_w = \frac{S_e'\left(S_e' + S_w\right)}{2\left(S_p S_r\right)} \times 100 \qquad \text{(eq. 7–9)}$$

where:
S_e' = optimum emitter spacing, ft (m)

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 less than S_e', then S_e' in equation 7–9 should be replaced by S_e.

For a MI system with spray emitters, P_w, can be computed by equation 7–10.

$$P_w = \frac{\left[A_s + \left(\frac{S_e'}{2} \times P_S\right)\right]}{S_p S_r} \times 100 \qquad \text{(eq. 7–10)}$$

where:
A_s = estimate of the soil surface area wetted per sprayer from field tests with a few sprayers, ft^2 (m^2)
P_S = perimeter of the area directly wetted by the test sprayers, ft (m)
$1/2\ S_e'$ = half the S_e' values for homogeneous soils (table 7–14), ft (m)

No single accurate 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, which contradicts the primary MI objective of maintaining a small soil volume at near constant soil moisture. For widely spaced crops, such as vines, bushes, and trees, a reasonable design objective is to wet at least a third and up to a half of the horizontal cross-sectional area of the root system. In areas that receive supplemental rainfall, designs that wet less than a 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 feet (1.83 m) apart, the P_w may approach 100 percent.

A relationship may exist between potential production and P_w for systems providing full plant water requirements, but currently data are too few to enable plotting specific curves for potential crop production versus P_w.

(e) Managing irrigation water requirements

In determining the depth or quantity of water to be applied at each irrigation and the frequency of irrigation, the concept of management-allowed deficit, the amount of plant canopies, the average peak daily evapotranspiration rate, and the application efficiency of the low quarter of the area should be considered. The management allowed deficit (MAD) is the desired soil moisture deficit (SMD) at the time of irrigation; the SMD is the difference between field capacity and the actual moisture available at any given time.

The MAD is expressed as a percentage of the available water-holding capacity of the soil or as the corresponding SMD 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 SMD equals the MAD. With drip irrigation, the SMD is kept small between irrigation. In arid areas, irrigation usually replaces the small SMD. In humid areas, however, irrigation should replace less than 100 percent of the SMD to provide soil capacity for storing moisture from rainfall.

The plant canopy is the area of land surface shaded in which the vegetation intercepts radiation rays.

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 rootzone, or required for leaching, to the average depth of irrigation water applied. The average low-quarter depth infiltrated is the average of the lowest 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 SMD 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.

(f) Maximum net depth of water application

The maximum net depth of application (F_{mn}) is the depth of water needed to replace the SMD when it is equal to the MAD. The F_{mn} is computed as a depth over the whole crop area and not just the A_w; however, the percentage P_w, must be taken into account. Thus, for MI systems, F_{mn} can be computed by equation 7–11.

$$F_{mn} = (MAD)(WHC)(RZD)(P_w) \qquad \text{(eq. 7–11)}$$

where:

F_{mn} = maximum depth of application, in, (m)
MAD = percentage of management allowed deficit
WHC = water-holding capacity of the soil, in/ft (m/m)
RZD = depth of the soil occupied by plant roots, ft (m)
P_W = percent area wetted

(g) Evapotranspiration rate

Many equations have been used to estimate crop water use based on climatic data (Howell and Meron 2006). NRCS procedures for calculating water use are found in NEH623.02, Irrigation Water Requirements. Chapter 2 recommends using the Penman-Monteith equation, which uses evapotranspiriation from a reference crop (ET_o) and modifies it for the specific crop by use of a crop coefficient (K_c).

The crop evapotranspiration (ET_c) estimates for DI and SDI designs can be expressed in terms of average peak daily ET_c, inches per day for the month of greatest water use by multiplying ET_o by K_c for specific crops. Crop coefficients for various crops are given in FAO–56 (Allen et al. 1998) and NEH623.02. Equation 7–12a can be used to calculate the daily evapotranspiration using the calculated ET_o:

$$ET_c = ET_o \times K_c \qquad \text{(eq. 7–12a)}$$

where:

Et_c = crop evapotranspiration rate, in/d, (mm/d)
ET_o = reference evapotranspiration, short crop, (grass), in/d, (mm/d)
K_c = crop coefficient for specific crop

Under well-managed DI, nonbeneficial use of water (drainage in excess of leaching requirement, non-reused runoff) is reduced to a minimum and nearly eliminated with SDI (Phene et al. 1991). Transpiration by the crop plants accounts for practically all the water consumed. The consumptive use estimates developed from procedures in NEH623.02 require modification for drip irrigation design. The modification is a function of the conventionally computed evapotranspiration rate, frequency of wetting, and the wetted

area. A more detailed description of this process may be found in NEH623.0204, Crop coefficients. Once the crop reaches full canopy, the crop is considered to use full ET and no longer needs modification.

(h) Seasonal evapotranspiration rate

The seasonal evapotranspiration rate (ET_s) can be computed by summing up ET_c in equation 7–12b for the whole cropping season.

$$ET_s = \sum_{\text{Planting}}^{\text{Harvest}} K_c\, ET_o \qquad \text{(eq. 7–12b)}$$

where:
ET_s = seasonal evapotranspiriation, in/yr, (mm/yr)

Additional information on computing ET_s are found in the procedures described in NEH623.02

(i) Net depth of application

The net depth of application (F_n) for DI and SDI systems is the net amount of moisture to be replaced at each irrigation to meet the ET_c requirements. Normally, F_n is less than or equal to the F_{mn}. If less than F_{mn} is applied per irrigation, then F_n can be computed by equation 7–13.

$$F_n = ET_c I_{fc} \qquad \text{(eq. 7–13)}$$

where:
F_n = net depth of application, in (mm)
ET_c = peak daily evapotranspiration rate for the mature crop, in/d (mm/d)
I_f = maximum allowable irrigation interval, days

(j) Gross water application

The gross amount of water to be applied at each irrigation, (F_g), includes sufficient water to compensate for the system nonuniformity and unavoidable losses and to provide for salt leaching. The peak-use-period transpiration ratio (T_R), the emission uniformity, and the leaching requirement ratio are included in F_g. The T_R is the ratio of the average (ET_c) to the total water applied. Values of T_R, to compensate for unavoidable deep percolation losses are (table 7–15):

- T_R is equal to 1 for crops with roots deeper than 5 feet (1.52 m) in all soils except very porous gravelly soils, for crops with rootzones between 2.5 and 5 feet (0.76 and 1.52 m) deep in fine- and medium-textured soils, and for crops with rootzones less than 2.5 feet (0.76 m) deep in fine-textured soils.
- T_R is equal to 1.05 for crops with deep rootzones in gravelly soils, for crops with medium rootzones in coarse-textured (sandy) soils, and for crops with shallow rootzones in medium-textured soils.
- T_R is equal to 1.10 for crops with medium rootzones in gravelly soils and for crops with shallow rootzones 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 7–14.

Table 7–15 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 course	Coarse	Medium	Fine
Arid				
<2.5 ft (.75 m)	1.15	1.10	1.05	
2.5 to 5.0 ft (.67–1.5 m)	1.10	1.10	1.05	1.05
>5.0 ft (1.5 m)	1.05	1.00	1.05	1.00
Humid				
<2.5 ft (.75 m)	1.35	1.25	1.15	1.10
2.5 to 5.0 ft (.67–1.5 m)	1.25	1.20	1.10	1.05
>5.0 ft (1.5 m)	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

$$EU = 100\left(1.0 - \frac{1.27CV}{\sqrt{e}}\right)\frac{q_n}{q_a} \times 100$$

(eq. 7–14)

where:
EU = design emission uniformity, %
e = number of emitters per plant (>1)
CV = 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, gal/h (L/h)
q_a = average emitter discharge (of all the emitters under consideration), gal/h (L/h)

The leaching requirement ratio (L_R) is described later.

The gross amount of water to be applied at each irrigation, F_g, can be computed by equation 7–15a and 7–15b. When T_R >1/(1.0–LR) or LR<0.1, the F_g can be computed by equation 7–15a.

$$F_g = \frac{(F_n T_r)}{\left(\frac{EU}{100}\right)}$$

(eq. 7–15a)

when T_R <1/(1.0–LR) and LR > 0.1, the F_g can be computed by equation 7–15b.

$$F_g = \frac{F_n}{\frac{EU}{100} \times (1 - LR_t)}$$

(eq. 7–15b)

where:
F_g = gross application, in (mm)
F_n = net depth of water application, in (mm)
EU = emission uniformity coefficient, %
LR = leaching ratio

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 7–16.

$$F_{(gpd)} = K\left[\frac{S_p S_r F_g}{I_f}\right]$$

(eq. 7–16)

where:
$F_{(gpd)}$ = gross volume per day, gal/d,(m^3/d)
K = 0.623 for English units, (1.0 for Metric units)
S_p = plant spacing, ft (m)
S_r = plant row spacing, ft (m)
I_f = maximum allowable irrigation interval, d

The annual net depth of application, $F_{(an)}$, inch, to meet evapotranspiration requirements may be reduced by the effective rainfall during the growing season, (R_e), inch, and residual stored soil moisture from off-season precipitation, W_s, inch. The values R_e and W_s are subtracted from seasonal evapotranspiration requirements. The F_{an} for DI can be computed by equation 7–17.

$$F_{(an)} = (ET_s - R_e - W_s)$$

(eq. 7–17)

where:
ET_s = total seasonal crop evapotranspiration, in (mm)
$F_{(an)}$ = annual net depth, in (mm)
R_e = season effective precipitation, in (mm)
W_s = residual soil moisture, in (mm)

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.

(k) Seasonal irrigation efficiency

The seasonal transpiration (T_s) and seasonal irrigation efficiency (E_s) 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 T_R<1/(1.0–LR), E_s can be computed by equation 7–18.

$$E_s = EU$$

(eq. 7–18)

When T_R>1/(1.0–LR) to satisfy the leaching requirement, E_s can be computed by equation 7–19.

$$E_s = \frac{EU}{T_R(1.0 - LR_t)}$$

(eq. 7–19)

where:
E_s = seasonal irrigation efficiency, %
LR = leaching ratio
EU = emission uniformity, %

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. Local values of T_R determined by field experience should be used if available; otherwise, with good system design and scheduling, use the T_R values given in table 7–15. The higher T_R values given for humid areas account for untimely rainfall.

(l) Gross seasonal depth of application

The gross seasonal depth of application (F_{sg}) can be computed by equation 7–20.

$$F_{sg} = \frac{F_{an}}{E_s\left(1-LR_t\right)} \qquad \text{(eq. 7–20)}$$

where:
F_{sg} = gross seasonal application depth, in (mm)
F_{an} = annual net depth of application, in (mm)
E_S = seasonal irrigation efficiency, %
LR = leaching requirement ratio

(m) Gross seasonal volume

The gross seasonal volume (V_i) of irrigation water required for acreage under a MI system can be computed by equation 7–21.

$$V_i = \frac{F_{sg}\left(A\right)}{K\left(1-LR\right)\frac{E_s}{100}} \qquad \text{(eq. 7–21)}$$

where:
V_1 = gross seasonal volume, acre-ft (ha–m)
K = 12 for English units (1,000 for metric units)
F_{sg} = annual gross depth of application, in (mm)
A = area under the system, acre (ha)

(n) Plant response

Plant response results for MI-irrigated crops are extremely abundant and generally positive when compared to all conventional irrigation methods (American Society of Agricultural Engineers 1995). Crop yields and quality of crops irrigated by MI systems are usually higher than those obtained by other methods of irrigation (Phene 1995). Orchards and vineyards that have been irrigated by sprinkler or surface irrigation methods can be converted to DI or SDI. The root systems of most trees and vines will adapt to the smaller wetted area in a few weeks. Thus, the conversion should be made just before or during the low use or dormant season; the root system will then have time to adapt with little shock before the peak use period. Conversions made during the peak Et period should slowly change from the old system to the MI system because an abrupt transition can severely stress a mature orchard. In young orchards, conversions can be made at any time. If there is sufficient precipitation to wet the soil a few feet deep, plant roots will extend beyond the MI-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 MI where Pw is greater than or equal to 33 percent, but in high-wind areas, any root extension that resulted from natural precipitation would be helpful.

(o) Irrigation scheduling

Irrigation scheduling is a process to determine when to irrigate and how much water to apply based upon measurements or estimates of soil moisture or crop water used by the plant. Irrigation scheduling is an integral part of irrigation water management. It is described in depth in NEH652.0903. Irrigating with a microirrigation system can result in less water being applied to the crop than with other irrigation systems because:

- less deep percolation and runoff will increase the application efficiency
- decreased surface wetting will result in less soil evaporation

Irrigation scheduling with a microirrigation system often differs from scheduling with other irrigation systems. In other types of irrigation systems, the soil

moisture content is allowed to decrease, often significantly, between irrigations. With a microirrigation system, the soil moisture can be kept at a virtually constant level. Irrigations can occur daily, or even several times a day. By irrigating several times a day (high-frequency irrigation (HFI)), there is a higher probability of applying the correct amount of water.

In fields where salinity is a significant factor, small amounts of rainfall can push salts into the rootzone. Consideration of the combined effects of rainfall and salinity must be included in any irrigation schedule for microirrigation. This is described in more detail in the section on salinity.

(p) Optimum soil moisture levels

Optimum soil water levels can be maintained with a well-designed and managed MI system. Under frequent irrigation (and good management), the plant roots undergo little shock or stress from irrigation, and the soil water holding capacity is not exceeded. The roots can seek and remain in a constant favorable water and nutrient 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. A large volume of moist soil is not necessary to promote root extension and water uptake as long as an adequate amount of water is provided as the plants use it.

The performance of DI and SDI systems improves with the use of HFI scheduling (especially on coarse-texture) soils. This allows the frequent replacement of water used by evapotranspiration, helps maintain a small volume of soil at nearly constant soil matrix potential, and minimizes plant water stress.

(q) Soil 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 (fig. 7–12). Salt accumulation results from evaporation at the soil surface and plant water uptake that excludes some salts. Because MI does not wet the whole soil profile, the salt accumulation process can be magnified rapidly when low-quality water is used. By applying more water than the plants consume (leaching), most of the soluble salts can be leached below or pushed outside the rootzone. In arid and semiarid regions, it is somewhat difficult to avoid having some areas of salt accumulation. Leaching is absolutely necessary to achieve long-term successful irrigation (Hoffman et al. 1990). As the salinity of the irrigation water increases or if more sensitive crops are grown, leaching must be increased to maintain crop yields.

With MI, the most critical zones of salt accumulation are along the fringes of the wetted front (fig. 7–73). A light rain can leach these accumulated salts down into the zone of extensive root activity and, thereby, severely injure plants. To minimize this hazard, operate the MI system during rainy periods to prevent accumulated salts from being washed back into the rootzone By operating the system continually, salts are leached down and out of the rootzone. If rainfall is less than 6 to 10 inches per year (0.15–0.25 m/y), 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.

(r) Crop tolerance and yield

MI affords a convenient and efficient method for frequent irrigation that usually does not wet the plant leaves (except for microjet and microsprinkler used with agronomic crops). Applying frequent light irrigations keeps the salt concentration in the soil solution to a minimum. Daily applications and sufficient leaching keep the salt concentrations in the soil water at almost the same level as that of the irrigation water. This occurs because there is little drying and salt concentration between irrigations; therefore, the salts remain diluted. With DI and SDI, when irrigations are infrequent and the soil dries out, the salt concentration increases quickly because of the small wetted soil volume.

With adequate water quality and nutrient management, yields with DI and SDI are equal to or better than those with other methods under comparable conditions. With poor-quality water, yields are potentially better with DI and SDI because of the continuous high moisture content and frequent replenishment of water lost by ET_c. Frequent sprinkler irrigation might give similar results, but continuous wetting and drying with

saline water eventually causes leaf burn and defoliation of sensitive plants.

Knowledge of the electrical conductivity of the irrigation water (EC_w), dS/m (1 dS/m µ1 mmhos/cm), and the electrical conductivity of the saturated soil extract (EC_e) dS/m, is useful in determining crop tolerance to an irrigation water. The minimum (min) and maximum (max) EC are useful in estimating leaching requirements under MI. 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. If the entire rootzone were at this salinity, the plants would not extract water and growth would stop. Table 7–16 gives values for min and max EC, for various crops. These values were extrapolated from test data that gave 0, 10, 25, and 50 percent reductions in yield.

(s) Leaching requirement

Harmful soluble salts must be removed from the crop rootzone in irrigated soils if high crop production is to be sustained. However, long-term SDI experiments to reduce drainage outflow have shown that allowing salts to accumulate below the rootzone may not be detrimental to yield, as long as the salts are not allowed to return to the rootzone by a rising shallow water table (Phene et al. 1989; Phene and Ruskin 1995). In addition, high salt concentration in the lower portion of the crop rootzone can be tolerated by some plants by compensating for reduced water uptake from the highly saline zone by increasing water uptake from the low salinity zone (Shalhevet and Bernstein 1968).

In arid regions where salinity is a major problem, additional irrigation water must be applied for leaching. The graphical solution (fig. 7–74) relating the salinity of the applied water and the crop salt-tolerance threshold (table 7–16) can be used as guides to determine leaching requirement (LR) for irrigating crops with conventional irrigation systems. For example, with water having an $EC_w = 1.0$ and a spinach crop with a salt-tolerance threshold of 2.0 dS/m, the LR should be 0.10.

Figure 7–74 is based on a steady state salt balance or, in popular terminology, "what goes in must come out, and nothing comes from in between." The calculated

Table 7–16 Minimum (min.) and maximum (max.) values of electrical conductivity of soil extract (EC_e) for various crops

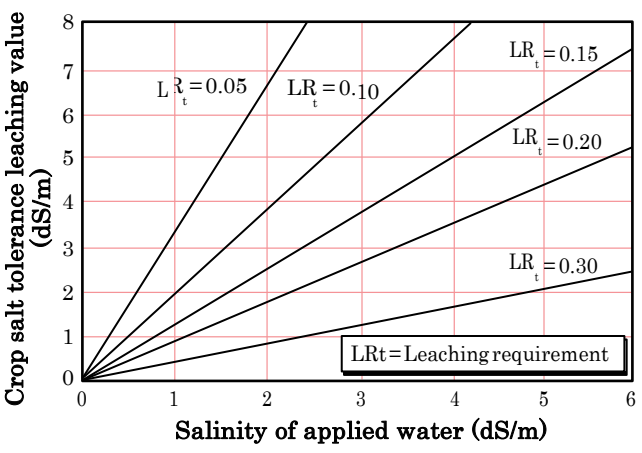
Crop	EC_e (mmhos/cm)		Crop	EC_e (mmhos/cm)	
	Min.	Max.		Min.	Max.
Field crops					
Barley	8.0	28	Corn	1.7	10
Cotton	7.7	27	Flax	1.7	10
Sugar beet	7.0	24	Broad bean	1.6	12
Wheat	6.0	20	Cowpea	4.9	8.5
Sorghum	6.8	18	Bean	1.0	6.5
Fruit and nut crops					
Date palm	4.0	32	Apricot	1.6	6
Fig, olive	2.7	14	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	41.7	6.5	Strawberry	1.5	4
Vegetable crops					
Beets	4.0	15	Sweet corn	1.7	10
Broccoli	2.8	13.5	Sweet potato	2.5	10.5
Tomato	0.9	12.5	Pepper	1.7	8.5
Cucumber	1.1	10	Lettuce	1.7	9
Cantaloupe	2.2	16	Radish	2.0	9
Spinach	3.2	15	Onion	1.2	7.5
Cabbage	1.0	12	Carrot	1.0	8
Potato	1.7	10	Bean	1.0	6.5

value of LR represents the minimum amount of water (in terms of a fraction of the applied water) that must pass through the rootzone to prevent salt buildup. When steady state salinity is achieved, the mean rootzone EC_e will be equal to EC_w. The actual LR, however, can be determined only by monitoring soil salinity.

The LR for a high-frequency system like MI is less restricting because the soil moisture remains relatively high. For relatively good quality water, LR will be very small and difficult to apply accurately so that it may be preferable to apply the leaching water on an annual or semiannual basis (if more information is needed, consult NEH623.02 or the US Salinity Laboratory). Salts that accumulate below the emitters can be flushed down continuously by frequent irrigations. If the LR ratio 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.

Another method of estimating LR is using the equations and graph developed by Rhoades (Rhoades and Loveday 1990). For microirrigation, the high-frequency equation and curve would normally be used. LR can be calculated using the relationships of crop salt tolerance and irrigation water salinity as shown in equations 7–22 and 7–23. Figure 7–75 is a graphical solution of these equations.

Figure 7–74 Leaching requirement (LR) as a function of the salinity of the applied water and the salt-tolerant threshold value of the crop (adapted from Hoffman and Van Genuchten 1983)



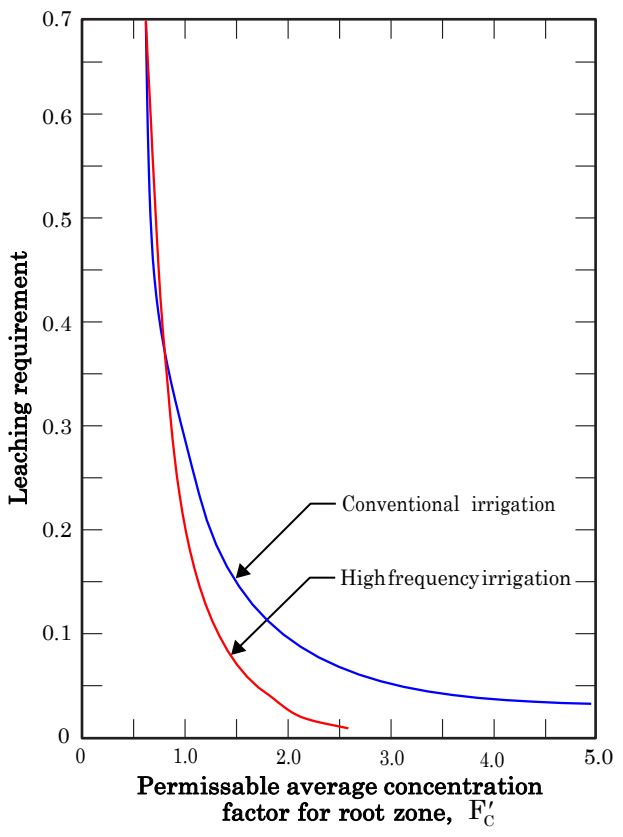
$$F'_c = \frac{\text{Salt tolerance of crop}\left(EC_t\right)}{\text{Electrical conductive of irrigation water}\left(EC_w\right)} \qquad \text{(eq. 7–22)}$$

High-frequency irrigation:

$$L_r = \frac{0.1794}{F'c^{3.0417}} \qquad \text{(eq. 7–23)}$$

Complete uniformity of leaching is assumed in this type of assessment of the leaching requirement. In actuality, such uniformity is seldom attained in field practice, and specific allowance should be made for each factor that causes less than perfect efficiency.

Figure 7–75 Relationship between permissible average concentration factor for the rootzone (F'_c) and the leaching requirement (LR) (adapted from Rhoades and Loveday 1990)



(t) Drainage disposal systems

Depending on the region under consideration, drainage may be practiced in humid areas to remove or control excess ground water to improve trafficability or crop management. In arid areas, it is used to control salinity. This section only relates to the control of salinity in arid and semiarid regions.

The collection and disposal of drainage flows from irrigation and rainfall is an important long-term management consideration in irrigated areas in terms of farm profitability, crop health, and overall water quality on and off the farm. Irrigation drainage includes surface runoff and deep percolation from precipitation and applied water. Under normal MI operating conditions, surface runoff and excessive percolation during irrigation does not usually occur. However, in arid and semiarid areas, periodic preseason flooding of fields may be necessary to leach accumulated salts from the rootzone. This practice may contribute to a perched saline water table that may produce a need for engineered drainage systems. Drainage from irrigation is often collected from drain laterals and reused several times with drip irrigation of increasingly salt tolerant crops such as cotton, asparagus, barley, and sugar beets (Ayars et al. 1986; Rhoades 1984, 1987, and 1989). Drainage disposal problems are complicated by the presence of toxic metal elements that accumulate in the food chain such as cadmium (Cd), mercury (Hg), lead (Pb), and Selenium (Se). These elements are often present in their stable form in soils originating from marine deposits, but tend to be oxidized to their soluble form with repeated irrigation. Drainage is a necessary component even with drip systems and must be evaluated on a case-by-case basis. Care should be also taken to check with State and local officials concerning regulations dealing with drainage water disposal and reuse.

(u) Frost protection

There are three methods of frost protection: undertree or canopy, overhead, and targeted. For undercanopy frost protection, the microsprinklers are used under the crop; this reduces the radiative heat loss from the soil surface. As the water freezes, additional heat is released as the water changes state (heat of fusion=80 cal/g of water or 335.2 J/g of water). The efficacy of frost protection depends on the amount of applied water (heat capacity of water = 1 cal/g/°C or 4.19 J/g/°C), the application rate of the system (minimum=1.0 in/h or 2.5 mm/h), evaporation rate, the dew point, and start-up temperatures.

With overhead frost protection, a thin film of water is kept over the targeted plant. As thin layers of ice form, the heat is released by the process (80 cal/g of water or 335.2 J/g of water). As long as the surface of the ice is kept wet, the ambient temperature near the leaf will not decrease below freezing. The minimum application rate of water needed to maintain this quasi-temperature equilibrium is 0.1 inches per hour (2.5 mm/h), assuming a highly uniform system.

For targeted frost protection, microsprinklers are placed within the targeted plant canopy. Similar to the overhead system, as water freezes, the heat of fusion is released protecting the plant canopy as long as water continues to be applied keeping the ice wet. This strategy reduces the required application rate of water allowing more acreage to be protected. However, this method is not recommended for young trees because weight of the ice may cause limb breakage.

623.0711 Design procedures

A step-by-step procedure is normally followed in designing a MI system. In MI, water, nutrients, and chemicals are transported in a pipe network to the points where the solution infiltrates the soil. The primary objective of good MI system design is to adequately irrigate and fertigate the least-irrigated plant. Uniformity of application depends on the emitter discharge uniformity. Nonuniform discharge may be caused by pressure differences resulting from friction loss and elevation, by emitter variation within manufacturing tolerances, and by clogging or wearing out of emitter parts. With SDI systems, back pressure exerted by the soil surrounding the emitter may be responsible for loss of discharge rate of water and chemicals dissolved in the water.

(a) Design criteria

Some important system design criteria that affect efficiency and performance of MI systems are:

- efficiency of filtration
- permitted variations of pressure head
- base operating pressure used
- degree of flow or pressure control used
- relationship between discharge and pressure at the pump or hydrant supplying the system
- allowance for temperature correlation for long-path emitters
- chemical treatment to dissolve mineral deposits
- use of secondary safety screening
- incorporation of flow monitoring
- allowance for reserve system capacity or pressure to compensate for reduced flow from clogging

A checklist of procedures in designing a MI system follows. Some of the steps are described in other chapters of NEH623, NEH652, and/or in earlier sections of this chapter.

- Inventory available resources and operating conditions. Include information on soils, detailed topographic field map, water supply, power source, crops, and operator's objectives following instructions in Chapter 3, Planning Farm Irrigation Systems.
- Determine water requirements to be met with a MI system, as described in Soil-Plant-Water Considerations.
- Determine appropriate type of MI system.
- Select and design emitters.
- Determine capacity requirements of the MI system.
- Determine appropriate filter system for site conditions and selected emitter.
- Determine required sizes of mainline pipe, manifold, and lateral lines.
- Check pipe sizes for power economy.
- Determine maximum and minimum operating flow rates and pressures.
- Select pump and power unit for maximum operating efficiency within the range of operating conditions.
- Determine requirements for chemical fertilizer equipment.
- Prepare drawings; specifications; cost estimates; schedules; and instructions for proper layout, operation, and maintenance.

(b) Emitter hydraulics

A general knowledge of the emitter design and operating theory for the various pressure dissipation methods helps in selecting an emitter. Most emitters can be classified hydraulically as long-path, laminar flow emitters, small-diameter orifice emitters, vortex emitters, porous tubes or tapes, pressure compensating emitters (PC), and recently, antisiphon, nonleak, pressure compensating emitters (CNL–PC). Emitters are used to dissipate the water pressure from the laterals.

The hydraulic characteristics of an emitter are related to the mode of fluid motion inside the emitter flow path and are characterized by the Reynolds number (R_e). Also, all emission devices regulate water flow by

energy dissipation through frictional resistance in their flow path according to the flow formula:

$$q = K_d (h)^x \qquad \text{(eq. 7–24)}$$

where:
q = emitter flow rate, gal/h (L/h)
K_d = flow coefficient, a proportionality factor that characterizes the dimensions of the emitter flow path
h = operating pressure head, ft (m)
x = emitter flow rate exponent, which characterizes the flow regime

In general, the values of K_d and x are available from the manufacturer, or they can be calculated by plotting q versus h on a log-log scale. The slope of the straight line is x, and the intercept at H=1 is K_d. The flow coefficient, K_d, is a proportionality factor that characterizes the physical dimensions of the emitter flow path. The emitter flow rate exponent, x, characterizes the flow regime of the emitter. The lower the x is, the lower the sensitivity to pressure variation. For instance, a fully pressure compensated emitter would have x = 0, the flow rate would be relatively constant within the specified range of operating pressures, and the uniformity of the system would be theoretically perfect. A turbulent flow emitter would have x = 0.5, and a laminar flow emitter would have x = 1. Table 7–17 gives the various types of flow regimes with the corresponding x values, associated common examples of emission devices, and advantages and drawbacks of the design. Various commonly used emitters and their flow equations are described.

Long-path emitters—Most of the head loss in a smooth long-path emitter (fig. 7–55) 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 drip 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 7–25.

$$l_e = \frac{\pi h g d^4}{98.6 q (\upsilon)} \qquad \text{(eq. 7–25)}$$

where:
l_e = length of the flow path in the emitter, ft (m)
h = working pressure head of the emitter, ft (m)
g = acceleration of gravity (32.2 ft./s^2) (9.81 m/s^2)
d = flow cross section diameter, in (mm)
q = emitter discharge, gal/h (L/h)
ν = kinematic viscosity of water, ft^2/s (m^2/s)

The spiral effects of flow at the entrance and other irregularities in the long-path emitters may create considerable turbulence. If turbulence exists, emitter head-loss characteristics computed by equation 7–25 would not be correct, and the emitter should be evaluated as a tortuous-path emitter. Some of the early long-path emitters could be opened for easy cleaning.

Tortuous- and short-path emitter—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) can be computed by equation 7–26.

$$q = 187 a c_q \sqrt{2gh} \qquad \text{(eq. 7–26)}$$

where:
q = emitter flow rate, gal/h, (L/h)
a = flow cross section, in^2 (mm^2)
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/s^2 (9.81 m/s^2)
h = working pressure head of emitter, ft (m)

Table 7–17 Common emitter types, their flow characteristics and regulation, advantages, and disadvantages

Emission device types	Flow characteristics	Flow regulation	Advantages	Disadvantages
Laminar (fig. 7–55)	Smooth, orderly, low-velocity flow	Energy dissipation accomplished by adjusting the length of the flow path	Simple, reliable, and inexpensive	Pressure sensitive, susceptible to clogging and temperature
Turbulent	Rapid flow in irregular and random motion	Energy dissipation accomplished by friction against walls and between fluid particles	Shorter and larger flow path than laminar flow types and high-flow velocity. Less sensitive to pressure variation and temperature	More expensive than laminar flow emitters
Vortex	Whirlpool effect creates a low pressure zone at its center where the outlet is located	Low pressure at the emitter outlet emits corresponding lower flow	Well-designed vortex emitter is less pressure sensitive than a turbulent flow emitter	Soil particles or other contaminants can easily clog extremely narrow emitter flow path
Pressure compensating (fig. 7–56)	Either laminar or turbulent flow devices	Uses the emitter inlet pressure with an elastomeric disk, diaphragm or water passage to modify the flow path size, shape, or length	Delivers relatively constant flow rate over a wide range of inlet pressures	Elastic properties of elastomeric materials may change with age. Thus, the elastomer used must be of high quality
Pressure compensating,-nonleak (figs. 7–57 and 7–76)	Turbulent flow devices with nonleak property that maintain low-pressure water in the laterals	Uses the emitter inlet pressure with an elastomeric disk, diaphragm or water passage to modify the flow path size, shape or length	Delivers relatively constant flow rate over a wide range of inlet pressures, and when inlet pressure drops to below 4–5 psi, the orifice shuts off maintaining water in the laterals and preventing soil ingestion	Elastic properties of elastomeric materials may change with age. Thus, the elastomer used must be of high quality
Thinwall dripperlines (fig. 7–58)	Turbulent flow with discrete emitter providing rapid flow in random motion	Energy dissipation accomplished by friction against emitter walls and between fluid particles	Less expensive than heavy wall tubes. Has the integrity of a discrete emitter so that the flow path does not collapse	In SDI application, thinwall dripperline may collapse when tape is empty and reduce its flow rate
Drip tapes (fig. 7–59)	Turbulent flow with flow in irregular and random motion	Energy dissipation accomplished by friction against tape walls and between fluid particles	Less expensive than thinwall dripperlines	In SDI application, flow path may collapse when tape is empty and reduce its cross-sectional area

Twin-chamber tubing—Most of the pressure head loss in twin-chamber tubing (fig. 7–59) occurs in the inner orifice. The q of twin-chamber tubing can be computed by equation 7–27.

$$q = 187 a c_q \sqrt{2g(h - h')} \qquad \text{(eq. 7–27)}$$

where:
q = emitter flow rate, gal/h, (L/h)
a = flow cross section, in^2 (mm^2)
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/s^2 (9.81 m/s^2)
h = working pressure head of the inner main chamber, ft (m)
h´ = working pressure head of the secondary chamber, ft (m)

Normally, the main and secondary chambers of twin-chamber tubing have the same diameter (although not in the example in fig. 7–59), and there may be as many as three to six orifices in the secondary chamber for each orifice in the main chamber. The h´ of the secondary chamber can be computed by equation 7–28.

$$h' = \frac{h}{1 + m^2} \qquad \text{(eq. 7–28)}$$

where:
h = working pressure head of the inner main chamber, ft (m)
h´ = working pressure head of the secondary chamber, ft (m)
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 vertical 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), which can be computed by equation 7–29.

$$q = 187 a c_q \sqrt{2g}\, h^{0.4} \qquad \text{(eq. 7–29)}$$

where:
q = emitter flow rate, gal/h, (L/h)
a = flow cross section, in^2 (mm^2)
c_q = coefficient for characteristics of the orifice; about 0.4
g = acceleration of gravity, 32.2 ft/s^2 (9.81 m/s^2)
h = working pressure head of emitter, ft (m)

Pressure compensating emitters—Pressure compensating emitters (fig. 7–56) 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. An early peculiar problem of compensating emitters was that the resilient material may have become distorted over a period of time and gradually squeezed off the flow, even though the pressure remained constant. Availability of more resilient materials has minimized, if not eliminated, this problem. The emitter discharge (q) can be computed by equation 7–30 for orifice and short-tube compensating emitters.

$$q = 187 a c_q \sqrt{2g}\, h^x \qquad \text{(eq. 7–30)}$$

where:
q = emitter flow rate, gal/h, (L/h)
a = flow cross section, in^2 (mm^2)
c_q = coefficient for characteristics of the emitter
g = acceleration of gravity (32.2 ft/s^2 (9.81 m/s^2))
h = working pressure head of emitter, ft (m)
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 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. 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 sensi-

tive to temperature. For emitters with flexible orifices that tend to expand under pressure, an approximate discharge (q), gallons per hour, (L/h), can be computed by equation 7–31.

$$q = 187\, a c_q \sqrt{2g}\left(\frac{h}{m'}\right)^{0.7} \qquad \text{(eq. 7–31)}$$

where:
a = flow cross section, in^2 (mm^2)
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/s^2)
h = working pressure head of emitter, ft (m)
m´ = 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 7–32.

$$q = 187 a c_q \sqrt{2g\frac{h}{m'}} \qquad \text{(eq. 7–32)}$$

where:
a = flow cross section, in^2 (mm^2)
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/s^2 (9.81 m/s^2)
h = working pressure head of emitter, ft (m)
m´ = number of orifices in series in the emitter

Pressure compensating nonleak (PC–CNL) emitters—The increasing use of SDI posed additional emitter requirements that resulted in the introduction of PC–CNL technology. SDI is subject to root intrusion and soil ingestion during hydraulic vacuum conditions (system turn off, undulating terrain, entrapped air) and is usually operated at high-irrigation frequency. The following features would typically be found in the new emitter design:

- *Antivacuum mechanism*—A built-in antivacuum mechanism prevents ingestion of soil particles into the dripperline, providing a critical protection against emitter plugging.
- *Wide pressure compensating range*—A wide pressure compensating range (7–60 lb/in^2, 0.49–4.22 kg/cm^2) maintains a constant uniform flow, which allows longer runs and steep terrains to be irrigated with high uniformity.
- *Optional nonleakage (CNL) mechanism*—CNL technology prevents system drainage when pressure is turned off at the end of each irrigation cycle. CNL ensures that the lateral remains full providing uniform water distribution during high-frequency irrigation.
- *Root intrusion barrier*—Barrier prevents roots from penetrating the dripper's mechanism.

The specific components and features of a PC–CNL emitter outlined are shown in figure 7–76.

Figure 7–77 shows examples of typical emitters in use today and how they are grouped into the various categories of emitters.

(c) Emitter selection criteria

Emitters dissipate the pressure in the pipe distribution network as the water flows from the lateral emitter lines into the atmosphere. The flow of water is driven by static pressure from the source to the soil through the various components of the system ending with the emitters in the field. The emitters in the field should distribute the irrigation water uniformly to the soil where it is extracted by the plants through the evapotranspiration process. The entire system responsible for the distribution of water is shown in figure 7–19. Besides providing uniform discharge, the “perfect” emitter device should incorporate the following features (adapted from Keller and Karmeli 1974; Boswell 1984; Howell et al. 1981):

- inexpensive
- easy to manufacture
- easy to install
- resistant to clogging
- totally pressure compensating (the flow exponent X=0)
- long lasting with constant performance over time
- nonleak below a pressure of 5 psi
- not affected by temperature and solar radiation
- reliable
- accurate

Figure 7–76 Components and features of a PC–CNL emitter *(courtesy of Netafim Irrigation)*

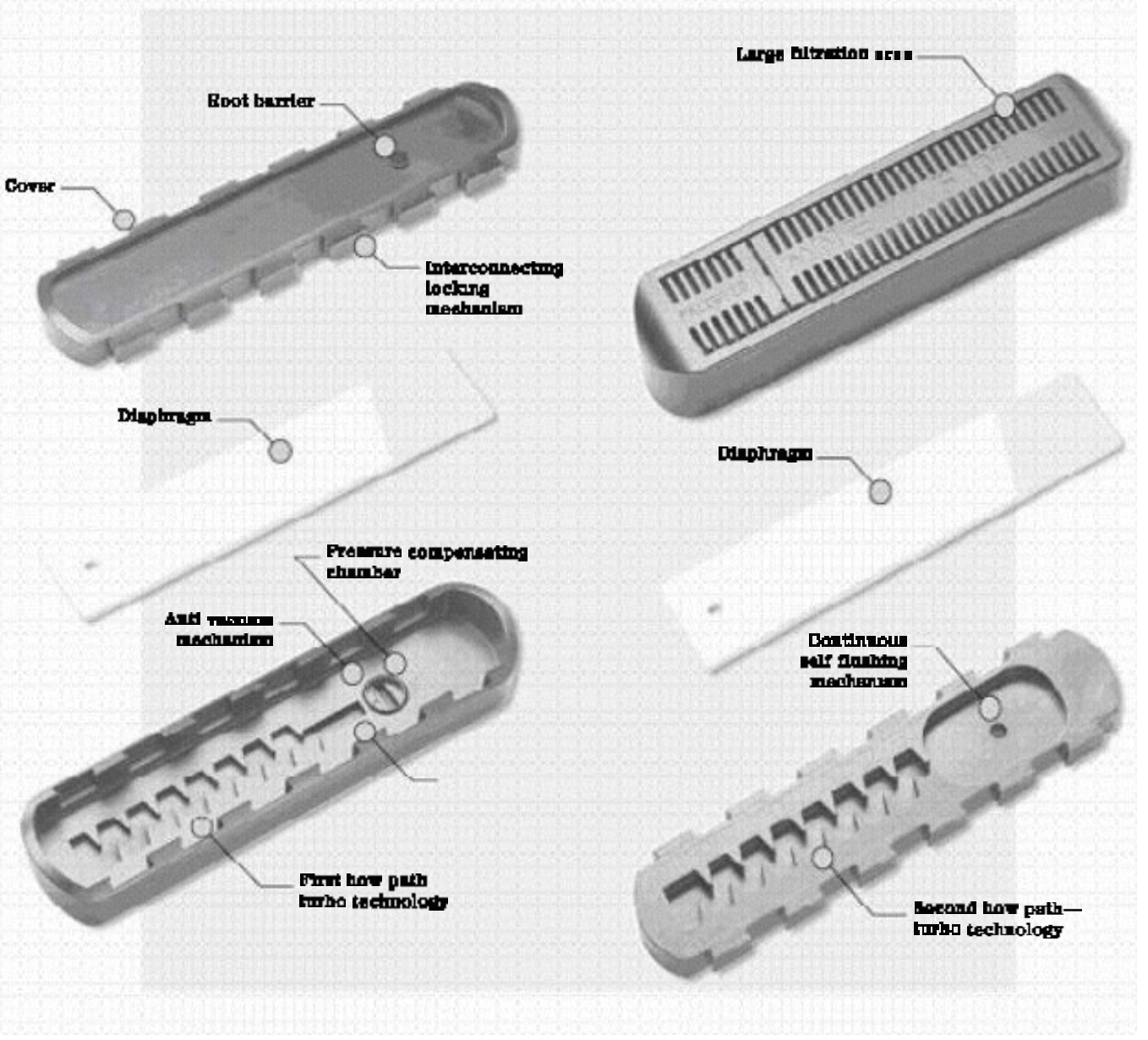
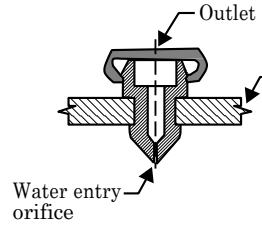
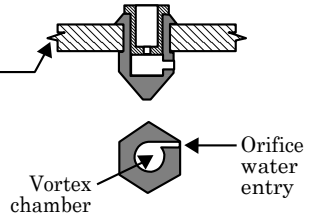


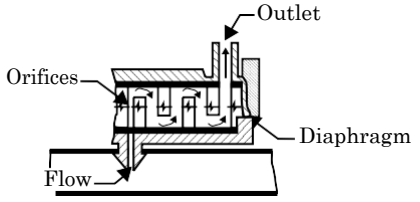
Figure 7–77 Common emitters in use today



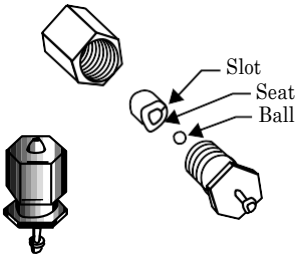
Orifice emitter



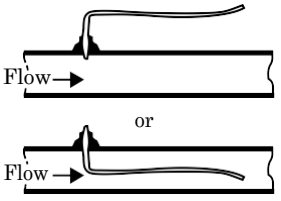
Orifice-vortex emitter



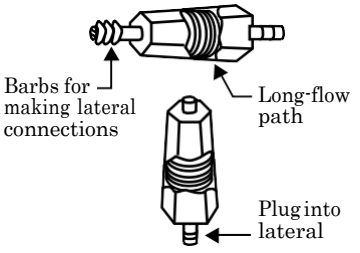
Emitter using flexible orifices in series



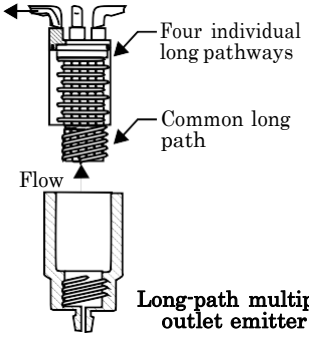
Ball and slotted seat emitter



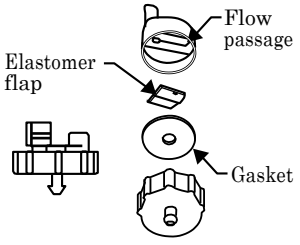
Long-path emitter small tube



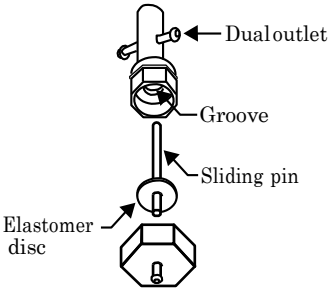
Long-path emitters



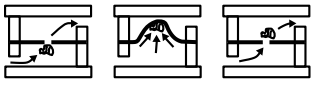
Long-path multiple-outlet emitter



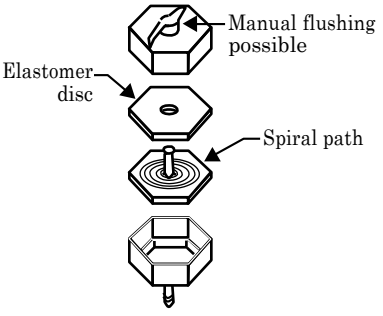
Groove and flap short-path emitter



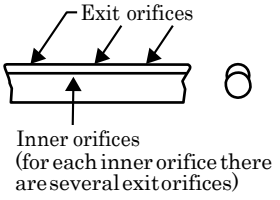
Groove and disc short-path emitter



Continuous flow principle of multiple flexible orfices



Compensating long-path emitter



Twin-wall emitter lateral

Until recently, most emission devices possessed only a few of these attributes simultaneously. Hence, it was necessary to consider which of these qualities were necessary for the specific application considered. Often, economics were the primary factor dictating the choice of emitter criteria, and complicated design factors were used to compensate for emitter deficiencies. Some site-specific applications may only require some of these features to be economically feasible; for example, pressure compensation may be useful on steep and/or undulating terrain or for very long laterals, but may not offer real advantages in a properly designed MI system on moderate flat terrain with a constant slope nearly equal to the friction loss of the laterals with distance.

Selecting emitters requires a combination of objective and subjective deductions. Emitter design and selection procedures require an assessment of discharge, spacing, and the type of emitter to be used: a discrete emitter lateral, a dripper line or tape, or a microjet or microsprinkler. This process is one of the most critical factors in the design of a MI 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.

The performance, advantages, and drawbacks listed in table 7–17 are also somewhat dependent on the manufacturer, designer, and management, especially for the long-term performance of the systems. Good design can often compensate for emitter hydraulic limitations; similarly, good irrigation system management can enhance the long-term performance of a system.

System efficiency of MI depends on the emitter selection and the design criteria. Some emitter characteristics that affect efficiency are:

- discharge rate variations caused by emitter variation within manufacturing tolerances
- closeness of discharge-pressure relationship to design specifications
- emitter discharge exponent
- possible range of suitable operating pressures
- pressure loss on lateral lines caused by the connection of emitters to the lateral
- susceptibility to clogging, siltation, or buildup of chemical deposit
- stability of discharge-pressure relationship over a long period

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 mainline and filtration system.

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:

Step 1: Evaluate and choose the general type of emitter that best meets the need in the area or volume to be wetted.

Step 2: Choose the specific emitter needed to meet the required discharge, spacing, and other planning considerations.

Step 3: Determine the average emitter discharge (q_a) and pressure head (h_a) requirements.

Step 4: Determine the allowable subunit pressure head variation (ΔH_s) for the desired emission uniformity (EU).

Two of the 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.

A reasonable design objective is to have enough emission points to wet at least a third and up to 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 less than or equal to 33 percent can usually be based on a 1 gallon per hour (3.785 L/h) 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 higher installation costs and lower water-use efficiency and lower installation costs, higher water-use efficiency, and added installation costs at a later date. Ideally, emitters should be long lasting and inexpensive; 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 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 drip 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—The primary features of an emitter that determine its plugging potential are the cross-sectional area of its flow channel and the amount of turbulence created within the flow channel. A large cross section gives plenty of room for contaminants to pass through without accumulating into clogs. A highly turbulent channel keeps soil particles suspended as they move through the emitters. When tapes become plugged, it can result from organic or inorganic sediment in the irrigation water, a vacuum condition inside of the drip tape causing soil particles to siphon back in through the outlet, or root intrusion and mineral buildup in the flow channel or at the outlet. Other emitter features also play important rolls in plugging resistance. Some drip tapes have discharge outlets that resist root intrusion. The design of the emitter inlet can also affect clog resistance. Finally, some emitters provide mechanisms that help remove clogs should they occur.

For the low discharge rates required in drip irrigation, an emitter's flow channel must be about 0.01 to 0.10 inch. 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:

- very sensitive, for a minimum passageway dimension of less than 0.023 inch (0.59 mm)
- sensitive, for a minimum passageway dimension of 0.024 to 0.060 inch (0.61 to 1.52 mm)
- relatively insensitive, for a minimum passageway dimension greater than 0.060 in (1.52 mm)

Velocities of about 14 to 20 feet per second (4.26 to 6.08 m) through the emitter passageway also reduce clogging.

Emitter discharges usually are rated at a temperature of 68 degrees Fahrenheit (20 °C) and a pressure of 15 to 30 psi (103.5–207 kPa). Line source tubing is usually rated at less than 15 psi (103.5 kPa). An orifice emitter has a flow cross section of about 0.008 to 0.024 inch (0.2–0.6 mm) and a flow capacity of 0.2 to 2.5 gallons per hour (0.757–9.462 L/h) and tends to clog if not managed properly. A long-path emitter has a flow cross section of about 0.02 to 0.055 inches (0.5–1.4 mm) and a flow capacity of 0.05 to 2.0 gallons per hour (0.189–7.570 L/h). 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. Table 7–18 gives equivalent dimensions for filtration requirements for use in selecting filters for specific emitters.

(1) Manufacturing variation

The variations in emitter passage size, shape, and surface finish that do occur are small in absolute magnitude, but represent a relatively large percent variation. Some emitters also use various elastomeric materials to provide a pressure compensating or flushing properties, 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 (CV) is a statistical description of how uniformly the flow rate of each manufactured emitter is in relation to one another. It is mathematically defined as the standard deviation divided by the average flow rate from a sample of emitters and calculated using equation 7–33.

$$CV = \frac{S}{\bar{q}} = \frac{\sqrt{\frac{q_1^2 + q_2^2 \ldots + q_n^2 - n\left(\bar{q}\right)^2}{n-1}}}{\bar{q}} \qquad \text{(eq. 7–33)}$$

Table 7–18 Filtration dimension equivalents for use in selecting filtration requirement for specific emitters

Filtration equivalents			
Screen size			
Mesh	inches	mm	Micron
5	0.1181	3.000	3000
10	0.0591	1.500	1500
20	0.0280	0.711	711
40	0.0165	0.420	420
80	0.0071	0.180	180
100	0.0060	0.152	152
120	0.0049	0.125	125
140	0.0042	0.105	105
150	0.0039	0.100	100
180	0.0035	0.089	89
200	0.0030	0.074	74
270	0.0021	0.053	53
300	0.0020	0.050	50
325	0.0017	0.044	44
600	0.0010	0.025	25

where:

CV	= emitter coefficient of manufacturing variation
$q_1, q_2, \ldots q_n$	= the individual emitter discharge rate values, gal/h (L/h)
n	= number of emitters in sample
q	= average discharge rate of the emitters sampled, gal/h (L/h)
S	= unbiased standard deviation of the discharge rates of the sample

The CV is a 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 CV is derived from the classic bell-shaped normal distribution curve shown in figure 7–78. As an example, for an emitter having a manufacturing CV = 0.06 (which is average, table 7–19) and $\bar{q}$ = 1.0 gallons per hour (3.785 L/h), 95 percent of the discharges can be expected to fall within the range of 0.88 to 1.12 gallons per hour (3.331 to 4.239 L/h), and the average discharge of the low 25 percent will be about 0.92 gallons per hour (3.482 L/h).

The small differences between what appear to be identical emitters cause significant discharge variations. CV values should be as low, or as close to zero, as possible. Most product CV_s measure between 1 and 20 percent. A CV of 5 percent or less is considered excellent. A classification of emitter manufacturing coefficient of variation is shown in table 7–19.

A lower standard is used for line source tapes 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 because the root system rapidly adapts itself to water distribution patterns.

Coefficient of variation values should be available from the manufacturer, or they can be estimated from the measured discharges of a sample set of at least 50 emitters operated at a reference pressure head and temperature.

(2) System coefficient of manufacturing variation

The system coefficient of manufacturing variation (CV_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 CV alone. The CV_s can be computed by equation 7–34.

$$CV_s = \frac{CV}{\sqrt{e'}} \qquad \text{(eq. 7–34)}$$

Figure 7–78 Bell-shaped curve describing the relative frequency of emission rate as a function of emitter flow rate

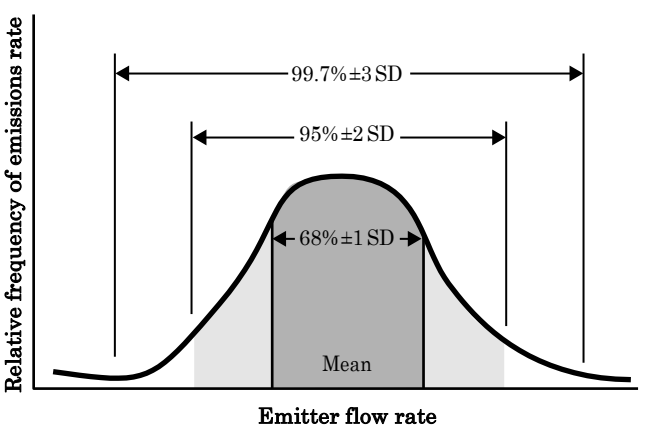


Table 7–19 Classification of emitter manufacturing coefficient of variation

Drip and spray emitters CVs	Classification
CV < 0.05	Excellent
0.05 < CV < 0.07	Average
0.07 < CV < 0.11	Marginal
0.11 < CV < 0.15	Poor
.15 < CV	Unacceptable
Line source tubing CVs	**Classification**
CV < 0.10	Good
0.10 < CV < 0.20	Average
0.20 < CV	Poor to unacceptable

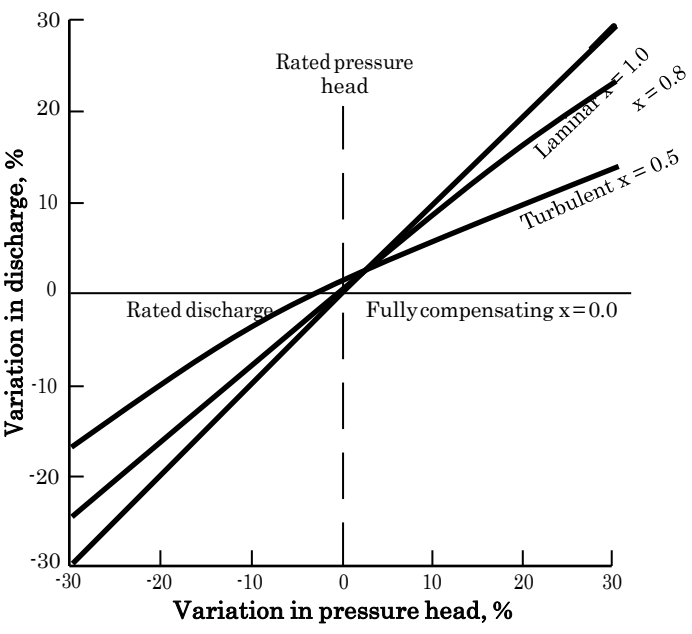
where:
CV = emitter coefficient of manufacturing variation
e´ = minimum number of emitters per plant, or 1 if one emitter is shared by more than one plant

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. 7–51e), 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 the CV is a property of the emitter alone, and CV_s is a property of the drip irrigation system as a whole.

(3) Relation of pressure to discharge

The relation between changes in pressure head and discharge is a most important characteristic of emitters and is critical to the design, management, and uniformity of the MI system. Figure 7–79 shows the graphical relationship for various types of emitters.

Figure 7–79 Relationship between percentage variations in discharge as affected by the percentage variation in pressure head for various emitters with different discharge exponents (Keller and Karmeli 1974)



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. Temperature, material fatigue, or both may affect the pressure compensating emitters.

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. However, nonpressure compensated emitters of various sizes may be placed along the lateral to meet pressure variations resulting from changes in elevation. The design practicality and economy of using emitters of more than one size in the field need 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. Figure 7–80 shows the flow variation from a typical laminar flow emitter.

In turbulent flow emitters, the change in discharge varies with the square root of the pressure 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. Figure 7–81 shows how pressure affects turbulent flow emitters.

Flow compensating emitters regulate flow to various degrees, and x may be less than 0.5. If flow regulation is absolute, x = 0.0. However, absolute flow regulation might be undesirable because if it ever became necessary to compensate for underdesign or for decreased

Figure 7–80 Flow rate/pressure relationship for a laminar flow emitter (X=1.00) *(courtesy of Netafim Irrigation)*

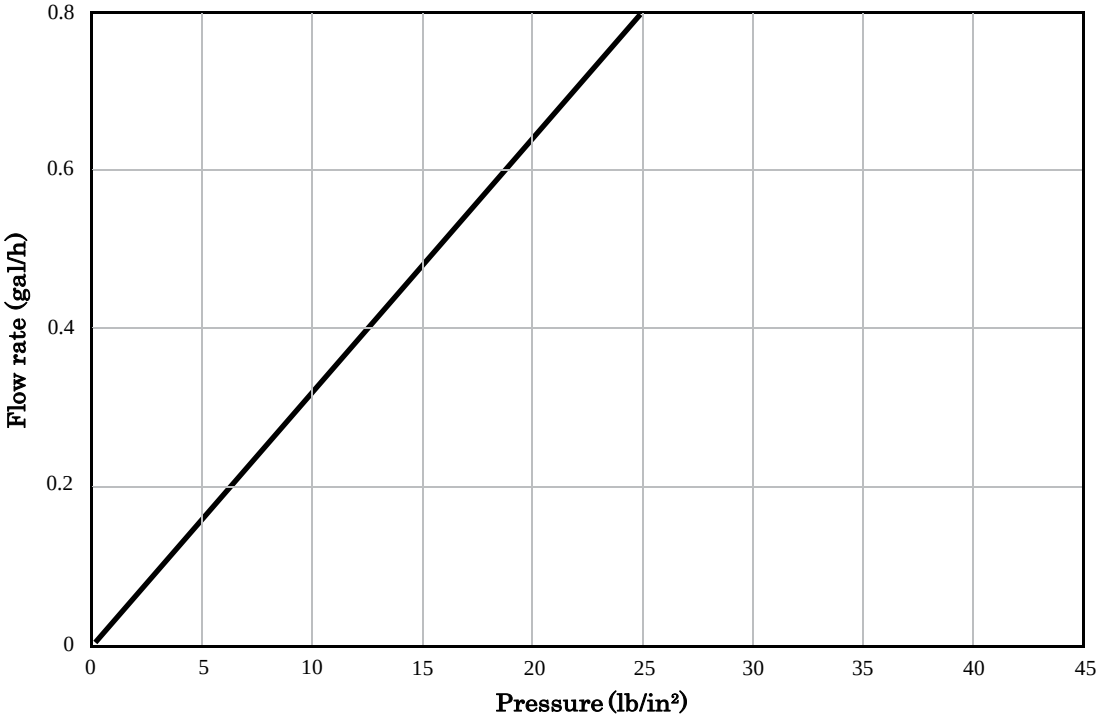
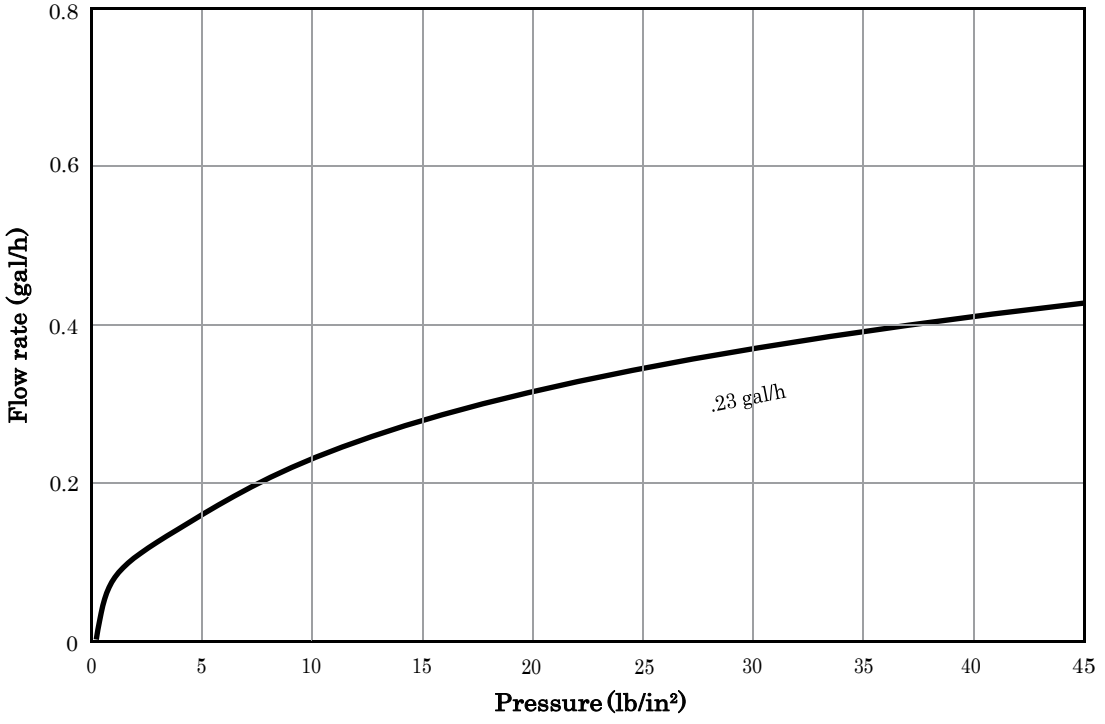


Figure 7–81 Flow rate/pressure relationship for a turbulent flow emitter (X=0.50) *(courtesy of Netafim Irrigation)*



emitter discharges resulting from slow clogging or emitter deterioration, increasing the pressure would not increase the flow. When x ranges between 0.3 and 0.4, flow is substantially regulated 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 or for very long laterals. Figure 7–82 gives an example of how pressure compensating emitters react to pressure changes.

(4) 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 mains, submains and lateral dripper lines lie in the sun. As the water moves through the system and changes temperature (usually warming), the uniformity of the discharge may also change. For fully laminar flow emitters, the flow rate is inversely proportional to the kinematic viscosity of the water, which in-turn varies inversely with temperature. Thus, the flow rate of water varies directly with temperature and must be corrected accordingly. Table 7–20 provides correction factors for computing emitter flow rates for temperatures other than the standard reference temperature of 68 degrees Fahrenheit (20 °C) and for flow exponents of x equals 0.6, 0.8, and 1.00 (Boswell 1984). In areas with hot climates, water temperatures at the end of the later-

Figure 7–82 Flow rate/pressure relationship for a pressure compensated flow emitter (X=0.0) (*courtesy of Netafim Irrigation*)

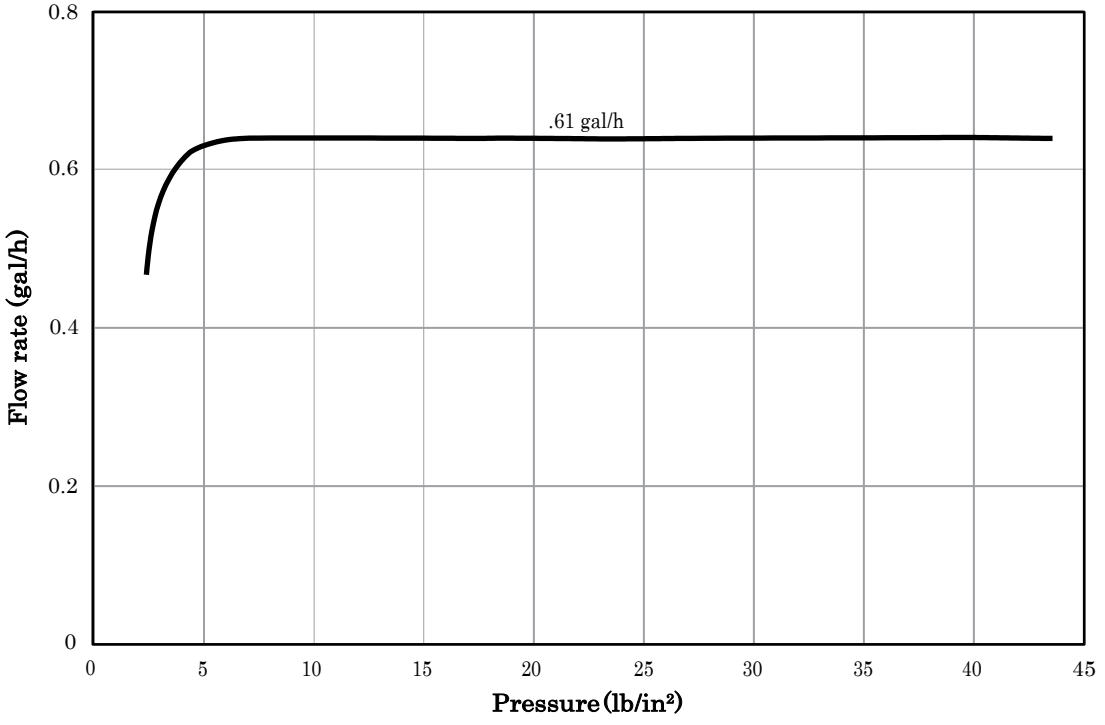


Table 7–20 Temperature correction factors for flow rate for emitters with flow exponents 0.6 ≤ x < 1.00 (Boswell 1984)

Water temperature, °C	Water temperature, °F	Correction factor flow exponent x=0.6	Correction factor flow exponent x=0.8	Correction factor flow exponent x=1.0
5	41	0.94	0.87	0.63
10	50	0.95	0.92	0.75
15	59	0.98	0.95	0.87
20	68	1.00	1.00	1.00
25	77	1.02	1.05	1.13
30	86	1.04	1.10	1.28
35	95	1.06	1.14	1.43
40	104	1.08	1.19	1.56
45	113	1.10	1.24	1.70
50	122	1.12	1.29	1.85

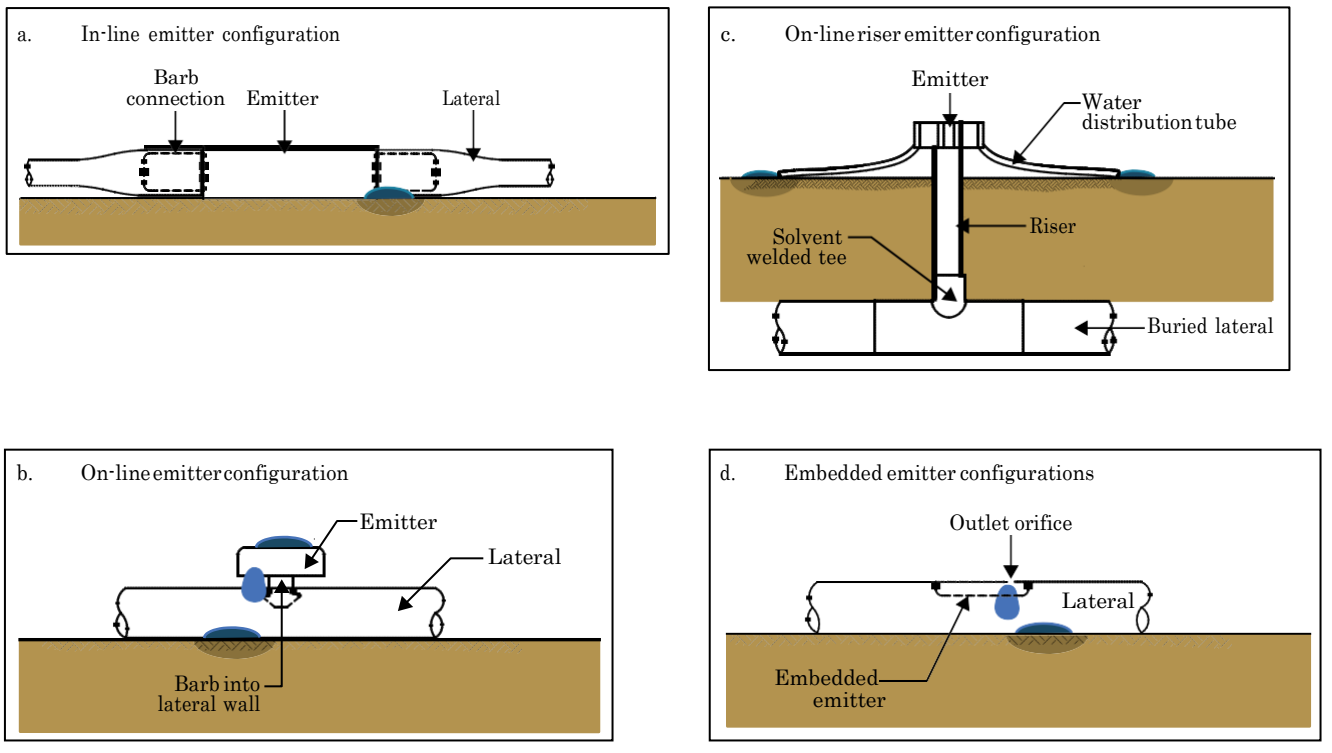
als have been measured as high as 140 to 145 degrees Fahrenheit (60–62.8 °C). In some cases, a small decrease in viscosity resulting from water warming as it flows toward the ends of laterals may partially compensate for the usual decrease in pressure.

One of the advantages of SDI is that the soil functions as a large heat sink for the dripperlines so that the water temperatures throughout the whole length of the laterals are usually constant and equal to the soil temperature. The deeper the mains, submains, and laterals are installed, the more constant the water temperature.

(5) Connection losses

The main types of lateral connections are in-line, on-line, on-line-riser, and embedded. Figure 7–83a–d shows these four lateral connections.

Figure 7–83 Lateral connectors



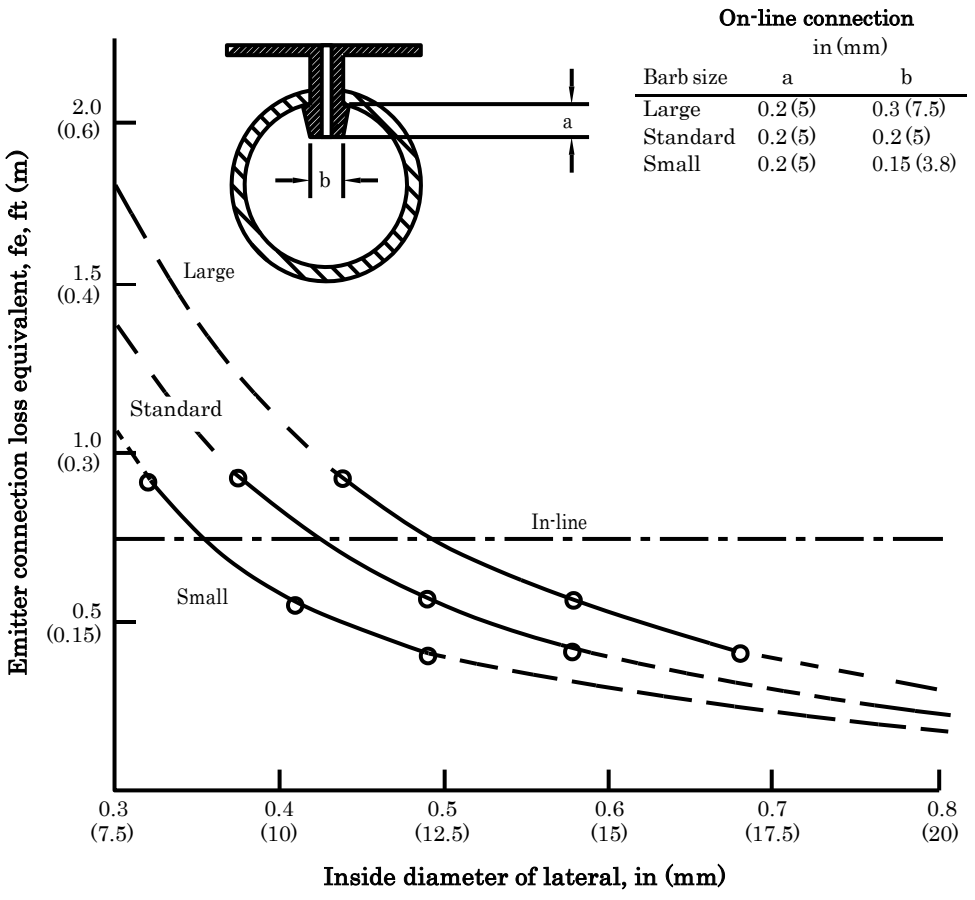
Configurations in figure 7–83a–c in-line, on-line, and on-line-riser lateral connections were used mostly in the past, but recently, configurations in on-line and embedded lateral connections have proved to be the most efficient and long lasting. On-line risers were used in quasi-subsurface applications, but this method was cost effective only when the emitter spacing was wide or where it provided agronomic advantages.

Stress cracking caused by emitter barbs stretching the lateral wall was a problem in on-line lateral connections. Excess stress caused premature aging at the joint, resulting in cracks and leakage, and in extreme cases, the emitters blew out. Connecting on-line emitters to the lateral with barbs in properly sized, smooth-edged, punched-out holes can prevent this potential hazard. In-line emitters could also 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 7–84 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. This approach can be adapted to integrated emitters, the type shown in figure 7–83d, using the relationship of the barb width to the inside lateral diameter as shown in equation 7–35 (Pitts, Ferguson, and Wright 1986; Watters and Keller 1978). Integrated emitter width range is from 0.25 inches on up. A typical width is 0.38 inches. Some manufacturers are now providing a coefficient (K. K_d, etc.) to account for the pressure loss associated with the friction caused by barbs.

$$F_e = Kb\left(D_i\right)^{-1.86} \qquad \text{(eq. 7–35)}$$

Figure 7–84 Emitter-connection loss (f_e) values for various sizes of barbs and inside diameter of dripper lines



where:
F_e = equivalent length of lateral, ft (m)
K = constant, 0.711 for English units (3.5 for metric units)
B = barb diameter, in (mm)
D = lateral diameter, in (mm)

(6) Emitter discharge rate, spacing, and installation depth of SDI systems

With SDI, the wetted soil radius is shorter in the SDI than in the DI system (fig. 7–71; Ben-Asher and Phene 1993). The implications are that under similar irrigation conditions:

- The wetted soil volume in the SDI system will be at a lower water content than in the DI system, and the leaching potential will be lowered.
- The surface area of soil available for root uptake of water and nutrients will be increased in the SDI system.
- The shorter wetted radius in the SDI system will allow closer emitter spacing than in the DI system, resulting in potentially improved wetted uniformity.

However, the surrounding soil exerts backpressure on the water discharged from the emitter, and if the emitter discharge rate exceeds the soil intake rate, water will find the path of least resistance and may come to the surface. Because of this, it is important to select emitters with as low a discharge rate as possible and increase the number of emitters per unit length. Depending on the crop to be irrigated, it is also important to install the SDI laterals as deep as possible. Root distribution studies have shown that with many field crops, vines, and tree crops, installation depths of 18 to 24 inches (0.45–0.60 m) promote deep rooting and prevent surfacing of the water (Phene et al. 1991). High frequency irrigation is also highly recommended with SDI to eliminate or minimize surfacing of the water and deep drainage below the rootzone (see figs. 7–67 and 7–68 for explanations of the effect of irrigation frequency on water movement in homogeneous and stratified soil, respectively). In coarse-textured soils and when time is a constraint, deep SDI installation may require a supplemental irrigation system to help germinate the crop. In areas with minimal precipitation and salty water, a supplemental irrigation system may also be needed to leach accumulated salts above the SDI laterals; however, irrigating with SDI during winter precipitation will usually suffice to provide adequate leaching of accumulated salts.

(7) Performance

Test data for a number of emitters are presented in table 7–21. All tests were made with clean water at a standard temperature of 68 degrees Fahrenheit (20 °C) on new emission devices obtained from retail outlets. A summary of the test results follows:

- The emitter discharge exponent (x) for the devices tested ranged from 0.11 to 1.0. Emitters having x values lower than 0.5 may be termed "pressure compensating." Pressure compensation is not a yes or no feature of emission devices; available devices had various degrees of compensation.
- Measured emitter coefficients of manufacturing variability (CV) ranged from 0.02 to 0.40. Most devices seemed to be manufactured with a consistency of CV Δ0.06.
- 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 7–21 provides a useful guide for the probable characteristics and important features of some types of emitters.

Table 7–21 Test characteristics of several emission devices[1]

Emission device[2]	TDR					Flushing ability
	X[3]	Cv[4]	113°	149°	MFPD6	
Orifice						
Vortex/orifice	0.42	0.07	0.92	0.88	0.024	None
Multiple flexible orifices	0.70	0.05	1.04	1.07	—	Continuous
	0.70	0.07	1.04	1.07	—	Continuous
Ball and slotted seat	0.50	0.27	1.15	1.21	(0.012)	Automatic
	0.49	(0.25)	0.83	0.79	(0.012)	Automatic
Compensating ball and slotted seat	0.15	0.35	0.85	0.81	0.012	Automatic
	0.25	0.09	0.90	0.89	(0.012)	Automatic
Capped orifice sprayers	0.56	(0.05)	(1.03)	(1.05)	0.04	None
	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	Automatic
	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 and flap	0.33	0.02	1.00	1.00	0.012	Automatic
Slot and 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. 7–26).
4 Emitter coefficient of manufacturing variation (eq. 7–33).
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.

(8) Discharge exponent

The emitter discharge exponent (x) characterizes the flow regime and discharge-versus-pressure relationship of the emitter. The emitter discharge (q) for most emitters or sprayers can be computed by equation 7–24. The discharge exponent (x) can be estimated using head-discharge relationship from field or manufacturer's data and equation 7–36.

$$x = \frac{\log\left(\frac{q_1}{q_2}\right)}{\log\left(\frac{h_1}{h_2}\right)} \qquad \text{(eq. 7–36)}$$

where:

q_1, q_2 = emitter discharges, gal/h (L/h)

h_1, h_2 = pressure heads corresponding to q_1, q_2, respectively, lb/in² (kPa)

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.

Example:

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 gallons per hour (3.785 L/h) at 10.0 psi (69.0 kPa), 1.34 gallons per hour at 20.0 psi (138 kPa).

Find: Discharge exponent (x) and pressure head (h) at which q equals 1.20 gallons per hour (4.542 L/h) (fig. 7–85).

Using equation 7–36:

$$X = \frac{\left[\log\left(\frac{1}{1.34}\right)\right]}{\log\left(\frac{10}{20}\right)}$$

$$= \frac{-0.127}{-0.301}$$

$$= 0.42$$

Graphically:

$$X = \frac{1.25\ \text{in}}{3.00\ \text{in}}$$

$$= 0.42$$

(d) Emitter operating characteristics

(1) 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 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 hours 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. The time of application, T_a, for the gross volume of water required per plant during the peak use period can be computed by equation 7–37.

$$T_a = \frac{F_{\left(\frac{gp}{d}\right)}}{e\left(q_a\right)} \qquad \text{(eq. 7–37)}$$

where:

T_a = set time, h/d

$F_{\left(\frac{gp}{d}\right)}$ = average volume of water required/plant/day during the peak use period, gal/d (L/d)

e = number of emitters per plant

q_a = average emitter discharge, gal/h, (L/h)

The maximum number of hours of operation per day should not exceed 90 percent of the available time (21.6 h/d). 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 hours per day (fig. 7–86). To determine N, select a reasonable T_a between 12 and 22 hours per day and compute a new q_a.

Figure 7–85 Graphical method for determining the discharge exponent (x) in a sample calculation

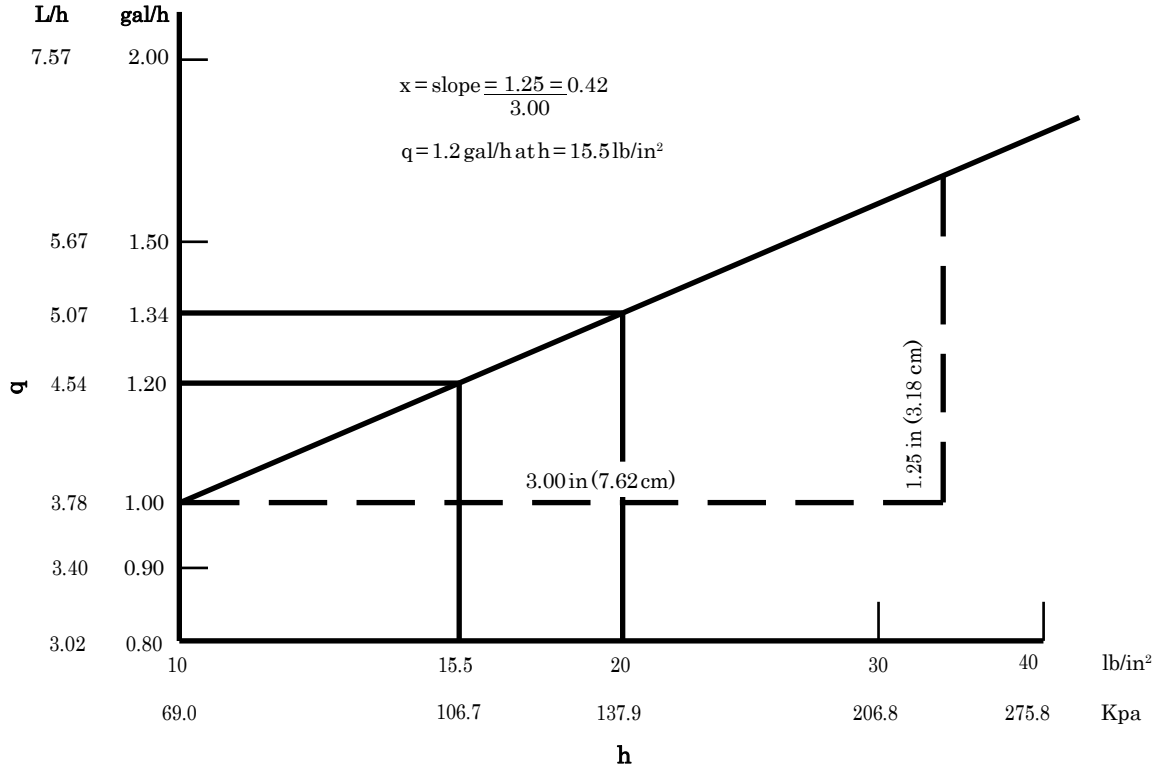
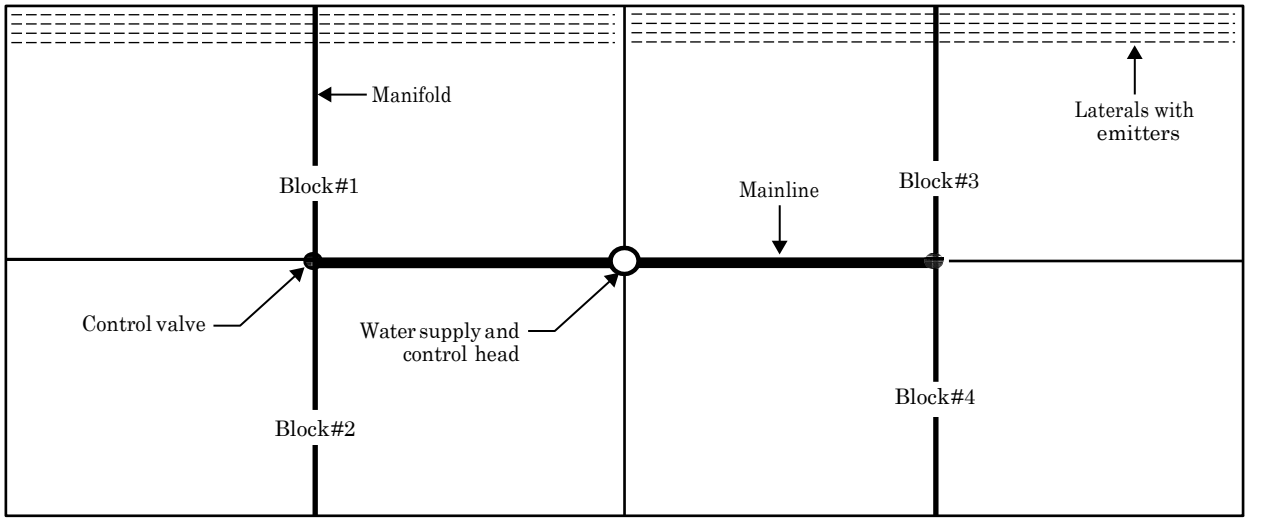


Figure 7–86 Typical two-station, split-flow layout for drip irrigation system with blocks I and III, or II and IV, operating simultaneously



When the preliminary value of T_a computed by equation 7–37 is greater than 22 hours per 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:

- If $T_a \cong 22$ hours per day, use a one-station system ($N = 1$), select $T_a \leq 22$ hours per day, and adjust q_a accordingly.
- If $T_a \cong 11$ hours per day, use $N = 2$, select $T_a \leq 11$, and adjust q_a accordingly.
- 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.

(2) Average pressure

Normally, published data for the emitter are a series of pressure heads versus discharges. For determining the average emitter pressure head, (h_a), for a desired average discharge, (q_a), the basic emitter discharge equation needs to be modified. The h_a for a given discharge can be computed by equation 7–38.

$$h_a = \left(\frac{q_a}{k_d}\right)^{\frac{1}{x}} \qquad \text{(eq. 7–38)}$$

where:

h_a = average emitter pressure head, ft, (m)
q_a = average emitter flow rate, gal/h, (L/h)
k_d = constant of proportionality (discharge coefficient) that characterizes each emitter
X = emitter discharge exponent

(3) Emission uniformity

Emission uniformity (EU) from all the emission points within a drip 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 7–39.

$$EU = 100\left(\frac{q_n'}{q_a'}\right) \qquad \text{(eq. 7–39)}$$

where:

EU = emission uniformity, %
q_n' = average discharge of the lowest 25 percent of the field-data discharge readings, gal/h (L/h)
q_a' = average of all the field-data emitter discharges, gal/h (L/h)

In the design phase, the variation expected in emission rates must be estimated by some analytical 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 (1974). 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 drip irrigation, which applies reduced amounts of water to the plant and irrigates only a part of the plant's root zone. In drip irrigation, underwatering is a greater hazard than overwatering. For a proposed design, an estimate of EU can be computed by equation 7–40a (for number of emitters greater than 1) or 7–40b (for the number of emitters equal to 1):

$$EU = 100\left(1.0 - 1.27\frac{CV}{\sqrt{e'}}\right)\frac{q_n}{q_a} \qquad \text{(eq. 7–40a)}$$

$$EU = 100\left(1.0 - 1.27CV_s\right)\frac{q_n}{q_a} \qquad \text{(eq. 7–40b)}$$

where:
EU = emission uniformity, %
CV = coefficient of manufacturing variation of the emitter, obtained from the manufacturer or by equation 7–37
CV_s = system coefficient of manufacturing variation (eq. 7–34)
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 versus pressure curve, gal/h (L/h)
q_a = average or design emission rate, gal/h (L/h)

The ratio of q_n/q_a expresses the relationship of minimum to average emission rate that results from pressure variation within the system. The 100 converts the ratio to a percentage. The factor in the middle adjusts for the additional nonuniformity caused by anticipated manufacturing variation between individual emitters.

The EU determines the uniformity of amounts of water emitted throughout a subunit 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:

- cost required installing systems with increased EU
- water and water-related costs
- sensitivity of crop yield and quality to nonuniform irrigation
- 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 equations 7–40a or 7–40b (depending on the number of emitters) are presented in table 7–22.

The minimum emitter discharge that will satisfy the desired EU value can be determined by solving equation 7–40 (7–40a or b, depending on the number of emitters) for q_n by using the q_a determined from equation 7–37 and the system coefficient of manufacturing variation (CV_s) for the selected emitter and layout.

(4) Allowable pressure head variation

The allowable pressure head variation (ΔH_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 7–87 is a schematic of the pressure head distribution in a simple subunit, where ΔH_s is the allowable pressure head variation; H_m is the manifold inlet pressure head; h_n is the pressure head that gives the q_n required to satisfy the design emission uniformity; h_a is the pressure head that gives the q_a; q_a is the average or design emitter discharge rate; q_n is the minimum emitter discharge rate. Figure 7–88 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 ΔH_s = 10 feet (3.04 m) when the pressure head, h_a, that gives the

Table 7–22 Recommend ranges of design emission uniformities (EU) [1]

Emitter type	Spacing ft, (m)	Topography	Slope %	EU range %
Point source on perennial crops	>13, (4)	Uniform	<2	90 to 95
		Steep or undulating	>2	85 to 90
Point source on perennial or semipermanent crops	<13, (4)	Uniform	<2	85 to 90
		Steep or undulating	>2	80 to 90
Line source on annual or perennial crops	All	Uniform	<2	80 to 90
		Steep or undulating	>2	70 to 85
Spray [2]	All	Uniform	<2	90 to 95
		Steep or undulating	>2	80 to 90

1 ASAE Engineering Practice Standard: ASAE EP405.1 (1988) Design and Installation of MI Systems
2 Keller and Bliesner, Sprinkle and Trickle Irrigation (2000)

Figure 7–87 Distribution of a pressure head in a subunit

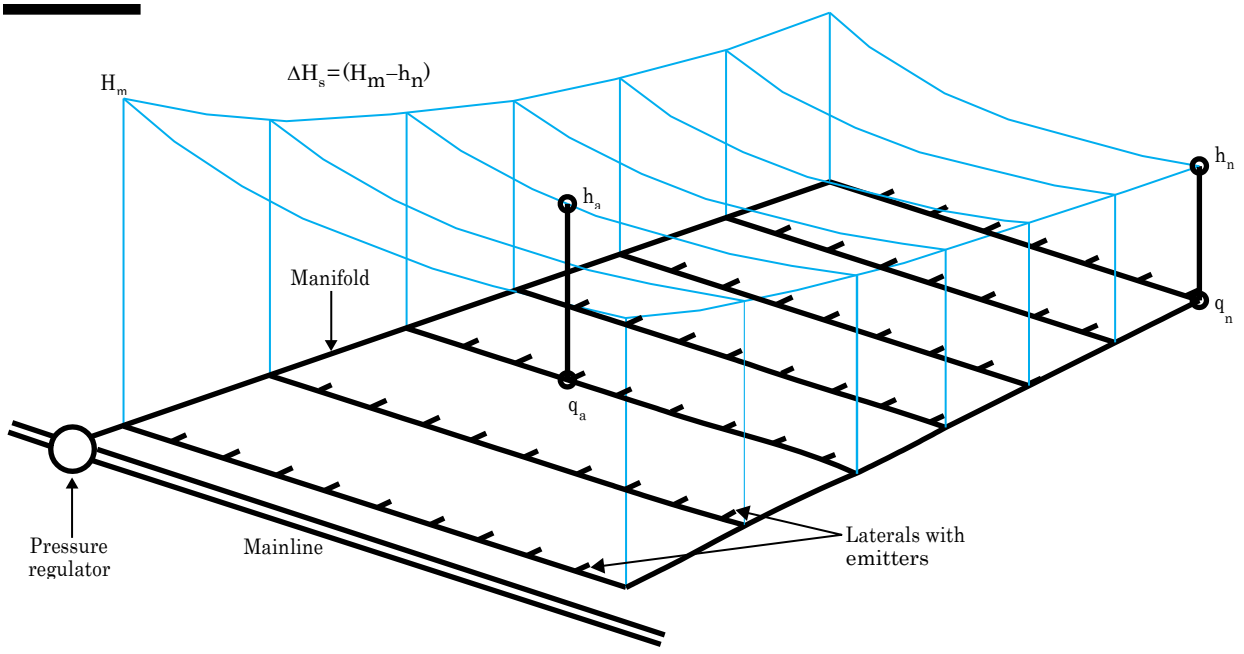
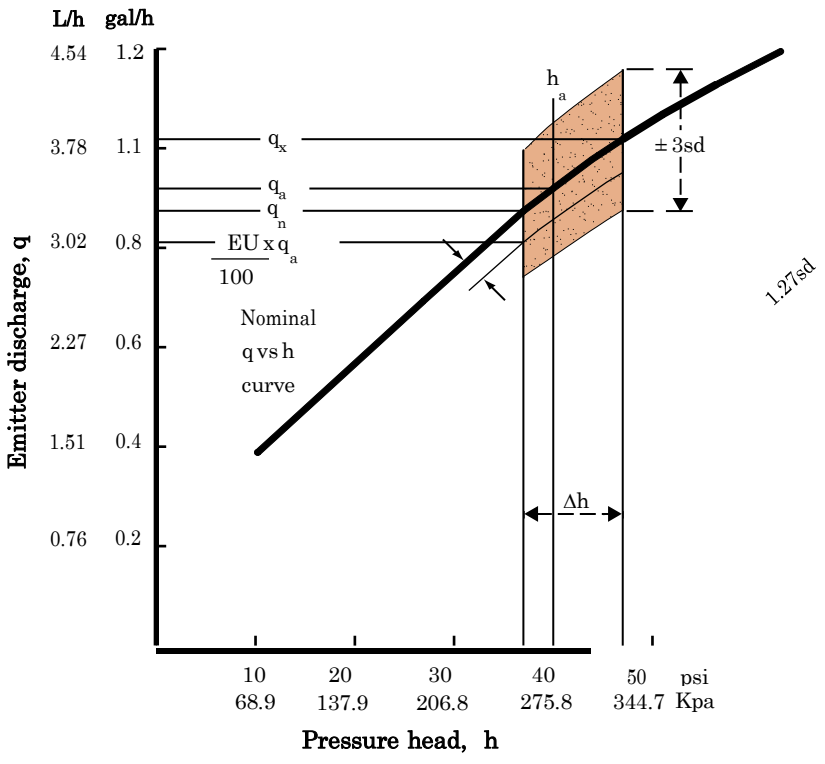


Figure 7–88 Combined effect of pressure head and manufacturing variations on discharges of individual emitters



average or design emitter discharge rate, (q_a), is 40 feet (12.16 m). This gives a subunit head-loss ratio of 0.25. The emitter characteristics are q_a equals 0.91 gallons per hour (3.444 L/h), emission discharge coefficient (x) equals 0.72, and manufacturer's coefficient of variation (CV) equals 0.033. The flow rate variation should be limited to 20 percent.

In figure 7–88, 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 discharges expected from a test sample of emitters at each possible operating pressure. The ΔH_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.

Example:

Determine emission characteristics and EU in a subunit.

Given: The emitter characteristics depicted in figure 7–88.

where:
q_a = 0.90 gal/h at h_a = 40 ft
Δh = 10 ft and h_n = 37.5 ft
therefore:
h_x = 47.5 ft
x = 0.72 and CV = 0.033

Find: The minimum and maximum nominal discharges q_n, and q_x, the emission uniformity, EU, of the subunit for e = 1, and the net design q.

From eq. 7–24

$$K = \frac{0.90}{(40)^{0.72}} = 0.0632$$

$$q_n = 0.0632(37.5)^{0.72} = 0.86 \text{ gal/h}$$

$$q_x = 0.0632(47.5)^{0.72} = 1.02 \text{ gal/h}$$

From eq. 7-40a

$$EU = 100\left(1.0 - 1.27\left(\frac{0.033}{\sqrt{1}}\right)\right)\frac{0.86}{.90} = 92\%$$

Therefore, the net design q is:

$$q = q_a \frac{EU}{100} = 0.82 \text{ gal/h}$$

The pressure head that gives q_n for the selected emitter (h_n) can be determined from equation 7–24. From h_a and h_n, the ΔH_s can be computed for design purposes by equation 7–41.

$$\Delta H_s = 2.50(h_a - h_n) \qquad \text{(eq. 7–41)}$$

where:
ΔH_s = allowable pressure head variation, ft (m)
h_a = pressure head that will give the q_a required to satisfy equation 7–38, ft (m)
h_n = pressure head that will give the qn required to satisfy equation 7–24 with the design EU, ft (m)

Maintaining the design EU requires keeping the pressure head between h_n and $(h_n + \Delta H_s)$ while differentials in both pipe friction and elevation are included. If the calculated ΔH_s is too small for economic design purposes, the options are to:

- select another emitter that has a lower coefficient of manufacturing variation (CV), discharge exponent (x), or both
- increase the number of emitters per plant (e)
- use a different emitter or rearrange the system to get a higher h_a
- relax the design EU requirement

(5) 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 7–42a and 7–42b.

$$Q_s = K\frac{A\,e\,(q_a)}{N\,S_p S_r} \qquad \text{(eq. 7–42a)}$$

where:
Q_s = system flow rate, gal/min (m^3/h)
K = conversion constant, 726 for English units (2,778 for metric units)
A = field area, acre (ha)
e = number of emitters per plant

N = number of operating stations
q_a = average or design emission rate, gal/h (L/h)
S_p = plant spacing in the row, ft (m)
S_r = distance between plant rows, ft (m)

For uniformly spaced laterals that supply uniformly spaced emitters.

$$Q_s = K \frac{A\ (q_a)}{N\ S_e S_l} \qquad \text{(eq. 7–42b)}$$

where:
S_e = spacing between emitters on a lateral, ft (m)
S_l = spacing between laterals, ft (m)

For computing total system capacity where line source tubing is used and the discharge rate is per 100 feet (30.4 m) of tubing, equation 7–42c can be used.

$$Q_s = K \frac{A\ e\ (q_a)}{N\ \ S^p} \qquad \text{(eq. 7–42c)}$$

where:
q_a = (q_a per 100 ft (m) of tubing)/100

(6) Pump operating time per season

The pump operating time per season (O_t) can be estimated by equation 7–43 with the gross seasonal volume (V_i) computed by equation 7–21 and the total system capacity (Q_s).

$$O_t = K \left(\frac{V_i}{Q_s} \right) \qquad \text{(eq. 7–43)}$$

where:
O_t = hours of operation, h
K = 5,430 for English units (2,778 for metric units)
V_i = gross seasonal volume, acre-ft (ha-m)
Q_s = total system capacity, gal/min (L/s)

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 maximum operation time of 21.6 hours per 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.

(7) Net water-application rate

The net water-application rate (I_n) is the water applied to the plants at the lowest discharge rate of the emission device. The net 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 I_n is a function of the minimum expected rate of emitter discharge (q_n) 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) in the system and can be computed by equation 7–44.

$$q_n = q_a \left(\frac{h_n}{h_a} \right)^x \qquad \text{(eq. 7–44)}$$

where:
q_a = average emitter discharge, gal/h (L/h)
h_a = average pressure head of emitter, ft (m)
x = emitter discharge exponent
h_n = minimum pressure for the subunit, ft (m)

If the friction head loss in a drip irrigation system is greater than the head gain from elevation drops, h_n can be computed by equation 7–45.

$$h_n = \left(H_m - \Delta H_m - \Delta h\right) \qquad \text{(eq. 7–45)}$$

where:
h_n = minimum pressure for the subunit, ft (m)
H_m = manifold inlet pressure head, ft (m)
ΔH_m = difference in pressure head along the manifold, ft (m)
Δh = difference in pressure head along the lateral, ft (m)

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 net application rate, I_n, can be computed by equation 7–46.

$$I^n = K\left(\frac{EU}{100}\right)\left(\frac{eq_a}{S_p S_r}\right) \qquad \text{(eq. 7–46)}$$

where:
K = 1.604 for English units (1.0 for metric units)
e = number of emitters per plant
q_a = emission point discharge, gal/h (l/h)
S_p = distance between plants in the row, ft (m)
S_r = distance between plant rows, ft (m)
I_n = net application rate, in/h (mm/h)

The maximum daily net water application that the system can apply in an emergency is $24\ h \times I_n$.

(8) 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 (qf) 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 7–5. Information about fertilizer compatibility, pH, and injection methods are also provided in NEH623.0706.

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) can be computed by equation 7–6.

Rate of chlorine or acid injection—The rate of injecting chlorine or acid depends on the system's flow rate. Liquid chlorinators are usually preferred over gas chlorinators because:

- 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.
- A gas chlorinator usually costs 4 to 10 times as much as a pump.
- 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.
- Most manufacturer's of drip 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), can be calculated by equation 7–47.

$$q_c = \frac{KCQ_s}{csg} \qquad \text{(eq. 7–47)}$$

where:
q_c = chemical injection rate, gal/h (L/h)
K = 0.006 for English units (0.36 for metric units)
C = desired dosage, ppm (mg/L)
Q_s = irrigation system capacity, gal/min (L/s)
c = concentration of the desired component in liquid chemical concentrate, %
sg = specific gravity of the chemical concentrate

(e) Pipeline hydraulics

This section contains data and information about the hydraulic aspects of pipe systems important in the design of drip irrigation systems.

(1) Friction loss in pipelines

Plastic is the predominant pipe material used for drip irrigation laterals, manifolds, and mainlines. The Hazen-Williams formula is the basis for many friction-loss calculations. Equation 7–48 can be used to calculate the head loss by the Hazen-Williams formula.

$$h_f = K\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} L \qquad \text{(eq. 7–48)}$$

where:
h_f = head loss from pipe friction, ft (m)
L = pipe length, ft (m)
K = conversion constant 10.50 for English units, (1.212×10^{10} for metric units)
Q = flow rate in the pipe, gal/min (L/s)
C = friction coefficient for continuous sections of pipe
D = ID of the pipe, in (mm)

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-inch (76.2 mm) or larger diameter pipes and discharges greater than 50 gallons per minute (189.25 L/min). Under these flow conditions, the Reynolds number (NR) is greater than 5 times 10^4, and the formula predicts friction loss satisfactorily. However, for the smaller pipe, such as the typical half inch (12.7 mm) lateral hoses used in drip irrigation systems, the Hazen-Williams formula with C = 150 underestimates the friction losses by about 30 percent. The half-inch (12.7 mm) hose exhibits characteristics equivalent to an average C value of about 130.

Another simple equation was developed by Watters and Keller that takes into account the low flow rates and the small diameters usually encountered with microirrigation. Equation 7–49a (hereafter referred to as the Keller equation) can be used to compute h_f for 5-inch (125 mm)-diameter or smaller plastic pipes and hoses. For D less than 5 inches (125 mm):

$$h_f = K\frac{Q^{1.75}}{D^{4.75}} L \qquad \text{(eq. 7–49a)}$$

where:
h_f = head loss from pipe friction, ft (m)
K = conversion constant, 0.00133 for English (7.89×105 for metric units)
L = pipe length, ft (m)
Q = flow rate in the pipe, gal/min (L/s)
D = ID of the pipe, in (mm)

Equation 7–49b can be used to compute h_f for larger diameter plastic pipe. For D greater than 5 inches (125 mm):

$$h_f = K\frac{Q^{1.83}}{D^{4.83}} L \qquad \text{(eq. 7–49b)}$$

where:
K = conversion constant, 0.0010 for English, (9.58×105 for metric units)

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 degrees Fahrenheit water flowing in smooth plastic pipe. Either the Hazen-Williams or the Keller equation may be used, but when using the Hazen-Williams, care must be taken to use the appropriate C factor. Recommended C values are shown in table 7–23.

Table 7–23 Hazen Williams C factors for various pipe sizes

C factor	Pipe diameter, in (mm)
130	≤ 1 (26)
140	< 3 (76)
150	≥ 3 (76)

(2) 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 fittings are:

- graphing friction loss versus flow rate
- expressing the added pressure head loss as the length of pipe (of the same diameter) that would give the same loss
- 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)

$$h_e = K_f \frac{V^2}{2g} \qquad \text{(eq. 7–50)}$$

where:
h_e = head loss caused by a specific fitting, ft (m)
K_f = friction head loss coefficient for a specific fitting
$\frac{V^2}{2g}$ = velocity head, which is the energy head from the velocity of flow, ft (m)

Graphs, equivalent lengths, or K_f values should be supplied by manufacturer's 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.

Emitter-connection loss equivalent lengths, (f_e), feet (m), representing losses for different barb sizes and lateral diameters are shown in figure 7–84, which 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 (m), can be computed by equation 7–51 and substituted for the actual length of the lateral with emitters (L´):

$$L' = L \frac{(S_e + f_e)}{S_e} \qquad \text{(eq. 7–51)}$$

where:
L´ = equivalent length, ft (m)
S_e = spacing between emitters on the lateral, ft (m)
f_e = emitter-connection loss equivalent lengths, ft (m)
L = lateral length, ft (m)

To calculate the lateral friction loss including emitter connection losses, substitute L´ for L in the friction loss equation being used.

(3) 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.

$$h_f = F\, h_{f\,no\,outlets} \qquad \text{(eq. 7–52)}$$

where:
h_f = friction loss adjusted for multiple outlets, ft (m)
$h_{f\,no\,outlets}$ = head loss of the lateral with emitters, ft (m)
F = reduction coefficient to compensate for the discharge along the pipe

Table 7–24 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 Keller equation (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.

The head loss along any multiple outlet pipeline that has uniform outlet spacing and discharge can be computed by equation 7–53.

$$h_{fx} = F\, h_f \left(\frac{X}{L}\right)^K \qquad \text{(eq. 7–53)}$$

where:
K = 2.852 for the Hazen-Williams equation and 2.75 for the Keller equation
h_{fx} = head loss from position x to the closed end, ft (m)
h_f = total head-loss of the pipe with emitters, ft (m)
F = reduction coefficient to compensate for the discharge along the pipe
X = distance from the closed end, ft (m)

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 obvi-

ously not true, but on pipelines that have 12 or more outlets, the error is less than 5 percent.

(4) Type, size, and location of air, pressure, and vacuum relief valves

Control of air in pipeline is a critical component of any hydraulic network. NEH623.0708(f) treats in detail the type, size, and location of air, pressure, and vacuum relief valves, and the reasons and needs for carefully selecting and installing these devices. Figure 7–19 suggests possible locations of these devices; however, site-specific conditions such as soil, topography, crops, and water quality will determine the final system design and use of these devices. Subsurface drip systems will require additional attention to the numbers, locations, and types of vacuum relief valves that are critical for preventing soil ingestion into the emitters.

(5) Flushing and maintaining flushing velocity

Guaranteeing long-lasting performance of MI systems is dependent on the maintenance ability to effectively flush mains, submains, and lateral lines to remove accumulated and settled sediments and microbiological materials. Some silt (2–50μm) clay (<2μm) particles will pass through most filters, aggregate together (sometimes with organic contaminants), and accumulate within the whole pipe network. Regardless of the water quality and water treatment, impurities will accumulate and settle out of the water forming deposits at the bottom of the lateral lines and emitter orifices. These deposits must be periodically flushed out of the whole system. Mains should be flushed first, then submains and manifolds, and finally the laterals.

Effective flushing is dependent on system design and more specifically on the ability to maintain a minimum lateral flushing velocity of 1 foot per second (0.304 m/s) per lateral, approximately 1 gallon per minute (3.785 L/min) at the end of a 5/8-inch (15.875 mm) lateral, or 2 gallons per minute (7.57 L/min) at the end of each 7/8-inch (22.23 mm) lateral (water squirting 2–3 feet (0.608–0.912 m) from the end of an open lateral will approximately provide the necessary flushing velocity). Several laterals can be flushed simultaneously provided that the pump capacity is sufficient to maintain the minimum flushing velocity.

Table 7–24 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	
	1.851	1.752		1.851	1.752
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 Keller equation and smooth-pipe curve on the Moody diagram or with equation 7–49a.

The average flow velocity in a pipe may be computed by using equation 7–54 (Boswell 1984).

$$V_a = K\frac{q}{D^2} \qquad \text{(eq. 7–54)}$$

where:
V_a = the average velocity, ft/s (m/s)
K = 0.409 for English units (1.273 for metric units)
q = the average flow rate, gal/min (L/m)
D = actual pipe inside diameter, in (mm)

Example: Find the average flow velocity for a pipeline using equation 7–54.

Given: D=4 inches and q_a = 350 gallons per minute

$$V_a = 0.4085\left(\frac{350}{4^2}\right)$$
$$= 8.94 \text{ fps}$$

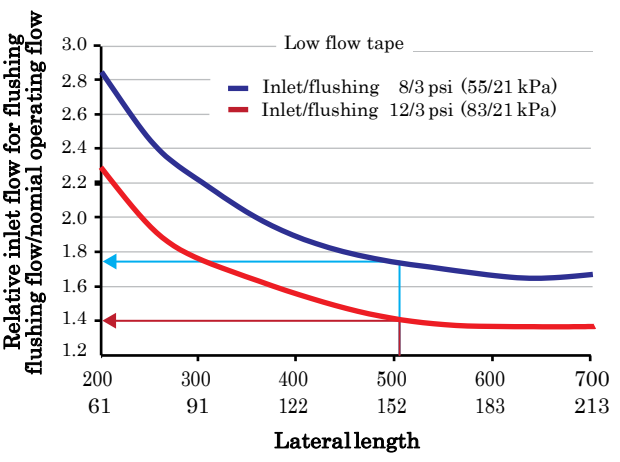
Several design and operating factors for flushing that need to be considered are:

- lateral material—thinwall drip tapes or heavy-wall drip tubes. PC or non-PC
- lateral installation depth—surface or SDI
- pump capacity and pressure—standard pump or variable speed pump, standard or adjustable pressure regulators
- water supply capacity—reservoirs, wells, or district turnout
- flushing design—single lateral flushing or flushing manifold
- mode and schedule of operation-—manual flushing or automated flushing
- pressure losses within system—manifold, mainline, submains, lateral, flushing valve, or manifolds, change in elevation, change in emitter discharge rate with pressure
- disposal of flushing water

A flushing system can be designed in a number of ways. It can range from an ideal system, which might include heavy wall PC drip line with a variable speed pump and an automated flushing manifold system that discharges flush water into a storage reservoir for later reuse to a very basic system with a manual flow control and manually flushing individual laterals with flush water applied to the field.

As an example use the "worst-case" scenario, assuming that if it can be designed and operated successfully, the other less requiring designs will be workable. Select a 5/8-inch (16 mm) drip-tape lateral (using Burt and Styles 1994) with a discharge Q=0.22 gallons per minute per 100 feet (0.833 L/30.4 m), at 8 psi (55.2 kPa), a lateral length of 500 feet (152 m) long, emitter flow rate exponent x=0.5, soil slope=0, and a flushing velocity of 1 foot per second (0.304 m/s) and a downstream pressure of 3 psi (20.7 kPa). Using the relationship in figure 7–89, we can determine the relative inlet flow for flushing (flushing flow/normal flow) equals 1.78 or a 78 percent increase in flow rate during flushing. This is a large increase in flow requirement, which the water supply and pumping station must be able to supply. If laterals are flushed one at a time, this is a small flow requirement (0.22 × 5 × 1.78 = 1.96 gallons per minute (7.42 L/min), an increase of 0.86 gallons per minute per lateral (3.251 L/min)), but if a manifold of 50 laterals is used, this is a 43 gallons per minute (162,755 L/min) increase in flow. Using figure 7–89, if the inlet pressure is increased to 12 psi (82.8 kPa), the relative inlet flow

Figure 7–89 Relative flow requirements during flushing for low flow tape. ID = 0.625 in (15.9 mm), Q=0.22 gal/min/100 ft at 8 and 12 psi (1.64 L/h/m at 55 and 83 kPa) inlet pressure (adapted from Burt and Styles 1994)



is reduced to 1.4 or a 40 percent increase in flow rate during flushing. This indicates that, depending on the type of flush manifold used, the supply manifold would need to be designed based on the conditions during flushing rather than normal operation. This could be the case with the design of many MI systems.

With SDI, flushing is more critical, so manifolds are almost always necessary. Single lateral flush valve can be used, but require frequent maintenance and replacement since they are exposed to animals, vandalism, and the environment (fig. 7–90). Flushing manifolds can be designed and installed below the level of the drip laterals to flush several laterals together. The flushing manifold system can and should be automated, and flushing can be scheduled as frequently as necessary. Flushing manifolds are also advantageous in balance flow and pressure for the irrigation block and supply water from both sides of the block in case of lateral pinching or blockage. A full design example of a flushing manifold will be included in the example section of system design.

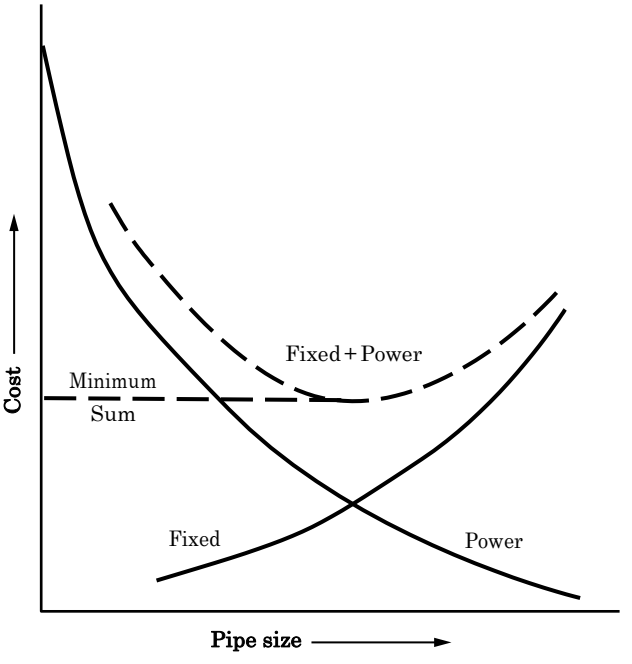
(f) Economic pipe size selection

The economics of drip irrigation is important to management in modern agriculture. The essence of economic selection of pipe size for a mainline is to find the minimum sum of fixed costs plus operating costs on either a present-worth or annual basis as presented pictorially in figure 7–91. 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. 7–92) was developed to simplify the pipe-sizing process for manifolds and mainlines for PVC pipe with lowest standard dimension ratio (SDR) (or pressure rating) IPS pipe sizes.

Figure 7–90 Example of end of line flushing valves

Figure 7–91 Influence of pipe size on fixed, power, and total costs

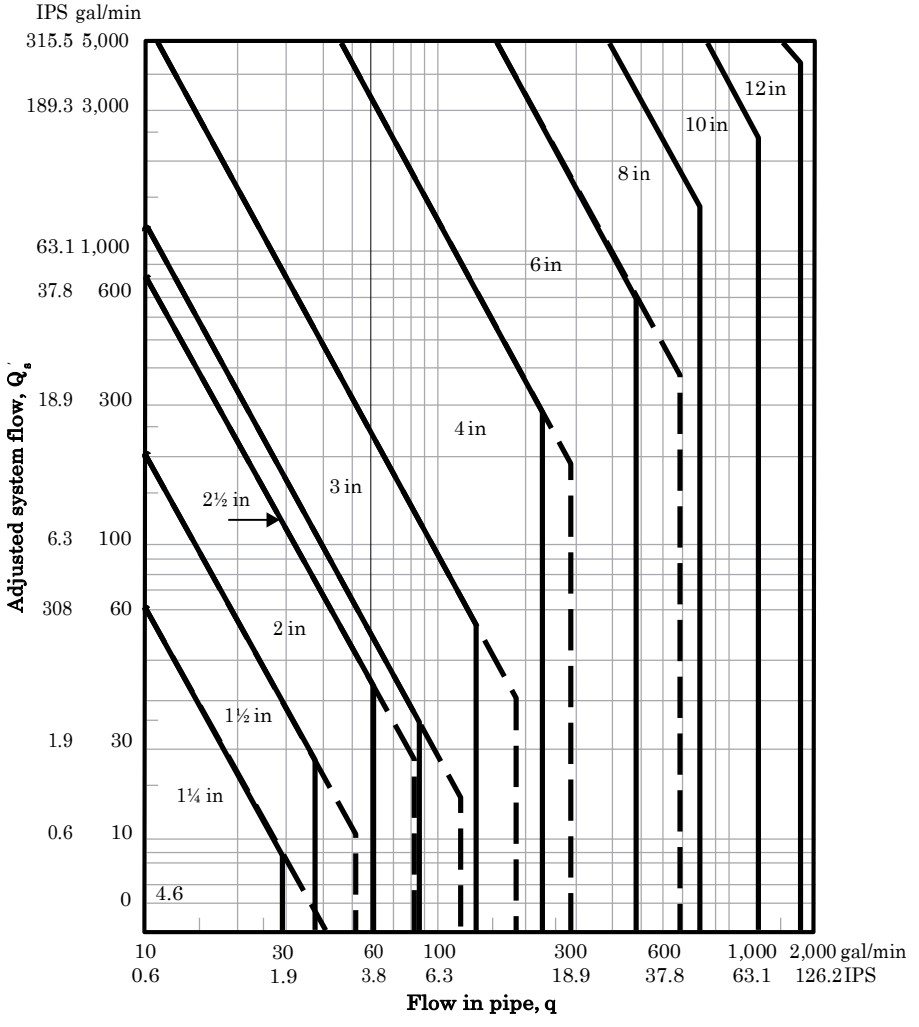


(1) Life expectancy costs

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 7–91.

The concept of value engineering represented by figure 7–91 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 7–92 Economic pipe size selection chart for polyvinyl chloride thermoplastic iron pipe size (IPS) pipe



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 7–25 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 7–55 and 7–56 for r does not equal i.

$$PW_r = \left[\frac{(1+r)^n - (1+i)^n}{(1-r)-(1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right] \quad \text{(eq. 7–55)}$$

and

$$EAE_{(r)} = \left[\frac{(1+r)^n - (1+i)^n}{(1+r)-(1+i)}\right] \times \left[\frac{1}{(1+i)^n - 1}\right] \quad \text{(eq. 7–56)}$$

The standard capital-recovery factor (CRF) was computed by equation 7–57.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \text{(eq. 7–57)}$$

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 7–55, 7–56, and 7–57. This rate is normally higher than bank interest rates because of the higher risks involved. For un-

Table 7–25 Present worth and annual economic factors for an assumed 9% 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]	0.206	0.613	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	3.671	3.859	3.954	3.995	4.000

1 Interest in 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

secured 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 h/U.S. gal (2.955 kW-h/L)
Gasoline:	10.5 BHP h/U.S. gal (2.069 kW-h/L) (water cooled)
Tractor fuel:	8.5 BHP h/U.S. gal (1.675 kW-h/L)
Butane-propane:	9.5 BHP h/U.S. gal (1.872 kW-h/L)
Natural gas:	8.5 BHP h/100 ft^3 (0.075 kW-h/m^3)
Electricity:	1.2 BHP h/kWh @ electrical meter

From table 7–25, some interesting observations can be made concerning the long-term effects of rising energy costs:

- Low i values de-emphasize high first costs, as indicated by low CRF.
- Low i values emphasize rising energy costs, as indicated by high PW (9%) and EAE (9%), but have less effect on constant energy costs, as indicated by PW (0%).
- High i values emphasize high first costs, but de-emphasize energy costs.
- Long useful life de-emphasizes high first costs, but emphasizes energy costs.
- Rising energy costs have a maximum effect when i is low and n is high.
- 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 7–25 can be used with the present annual power costs (E) and the cost of the irrigation system (C) to estimate the:

- present worth of the rising (9% per year) annual energy cost, E × PW (9%)
- equivalent annual cost (E´) of the rising (9% per year) energy cost E × EAE (9%)
- annual fixed cost of the irrigation system, C × CRF
- present worth of the constant energy cost, E × PW (0%)
- annual cost of the constant energy cost, E
- present worth of the irrigation system, C

(2) Economic pipe selection charts

Figure 7–92 was developed for PVC thermoplastic pipe with SDR of 32.5 or 125 psi (224.3 or 862.5 kPa). The solid and dashed vertical lines, respectively, represent 5 to 7 feet per second (1.52 to 2.13 m/s) velocity limitations. 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) is 0.100, cost per water horsepower per year (C_{whp}) is $100, and PVC pipe cost is $1 per pound ($2.205/kg). Obtain the ID and weight per foot (m) of pipe of each size being considered. This example shows construction of the line separating the 3- and 4-inch (76.2 and 101.6 mm) regions. The ID and weight of 3-inch (76.2 mm) SDR 32.5 pipe are 3.284 inches (82.4 mm) and 74.2 pounds per 100 feet (1.108 kg/m), respectively, and those of 4-inch (101.6 mm) SDR 41 pipe are 4.280 inches (108.7 mm) and 98.4 pounds per 100 feet. (1.470 kg/m), respectively.

Step 2: Determine the yearly fixed-cost differences between adjacent 3- and 4-inch (76.2 and 101.6 mm) pipes with CRF being 0.100:

$$0.100(\$98.4 - \$74.20) = \$2.42/100\text{ ft}\ (\$0.08/\text{m})$$

Step 3: Determine the water horsepower savings needed to offset the annual fixed-cost difference between adjacent 3- and 4-inch (76.2 and 101.6 mm) pipes with C_{whp} equaling $100:

$$\frac{\$2.42}{\$100.00} = 0.0242\text{ whp}/100\text{ ft}(0.0008\text{ whp/m})$$

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 gallons per minute (378 L/min) for the 3- and 4-inch (76.2- and 101.6 mm) pipe sizes:

$$h_{f(3,4)} = \frac{0.0242 \text{ whp/ft} \times 3{,}960}{100 \text{ gal/min}}$$

$$= 0.958 \text{ ft/l00 ft} (0.00958 \text{ m/m})$$

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 at emitter discharge (q) = 95 gallons per minute (360 L/min):

$$h_{f(a,b)} = \frac{h_{f(a)}}{100 \text{ ft}} - \frac{h_{f(b)}}{100 \text{ ft}}$$

$$h_{f(3,4)} = 1.34 - 0.38 = 0.96 \text{ ft/100 ft} (0.0096 \text{ m/m})$$

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 7–92. For the 3- and 4-inch (76.2- and 101.6-mm) PVC pipes in this example, the point is Q_s, 100 gallons per minute (378 L/min), and q is 95 gallons per minute (360 L/min).

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 feet per second (1.52 m/s) for each pipe size. For the 3-inch (76.2 mm) pipe, this is 132 gallons per minute (500 L/min), which is represented by the solid vertical line separating regions 3 and 4 of figure 7–92. Since velocity restrictions override economic considerations, the vertical line defines the boundary between the 3- and 4-inch (76.2 and 101.6 mm) pipe regions at a flow rate of 132 gallons per minute (500 L/min). The dashed extensions are for velocities of 7 feet per second (2.128 m/s).

The economic pipe selection chart for PVC thermoplastic IPS pipe with minimum acceptable SDR rating (fig. 7–92) is based on pipe cost at $1 per pound ($2.21/kg). C_{whp} is $100, and CRF is 0.100. The negative sloping lines represent all the possible Q versus 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 versus q values when the pipe size that is common to both lines is the most economical selection. Figure 7–92 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 mainline design are presented for drip and spray systems.

To use figure 7–92 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 7–58.

$$C_{whp} = \frac{(O_t)(P_{uc})(EAE_{(r)})}{\left[(E_p)\left(\frac{BHP}{P_u}\right)\right]} \qquad \text{(eq. 7–58)}$$

where:

C_{whp} = cost per water horse power, dollars
O_t = average pump operating time per season, h, eq. 7–43
$EAE_{(r)}$ = 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 7–25 or eq. 7–56
P_{UC} = unit cost of power, $/kW-h
E_P = pump efficiency
BHP = brake horsepower (kW)
P_u = unit of power

Next, determine the system flow-rate adjustment factor (A_f) by equation 7–59.

$$A_f = \frac{0.001C_{whp}}{(CRF)(P_c)} \qquad \text{(eq. 7–59)}$$

where:
A_f = system flow adjustment factor
CRF = capital recovery factor, table 7–25 or eq. 7–57
P_c = pipe cost, \$/lb (\$/kg)

The system flow rate for entering the economic chart (Q_s'), gallons per minute, is computed by equation 7–60.

$$Q_s' = A_f Q_s' \qquad \text{(eq. 7–60)}$$

where:
Q_s' = adjusted flow rate, gal/min (m^3/h)
Q_s = system flow rate under consideration, gal/min (L/min)

The constant 0.001 in equation 7–59 is the number that gives $A_f = 1$ with the economic factors used in developing figure 7–91. For economic pipe size selection charts developed from other economic factors, the constant must be changed so that A_f is 1 for the C_{whp}, CRF, and pipe cost per unit used.

The procedure using the economic design chart and mainline design strategy involves the following:

Step 1: Enter the vertical axis of figure 7–92 with Q_s', and select an economic pipe size for the q in each section of mainline pipe. (To hold velocities below 5 ft/s (1.52 m/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 equations 7–49a or 7–49b.

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 (m) by equation 7–61.

$$(H_{fe})_m = \sum_1^m h_f \Delta El \qquad \text{(eq. 7–61)}$$

where:
$\sum_1^m h_f$ = sum of the pipe friction losses between the pump and manifold inlet at m, ft (m)
ΔEl = difference in elevation between the pump and manifold m (+ is uphill to manifold and – is downhill), ft (m)

Step 4: Once the $(H_{fe})_m$ has been determined for the critical manifold, the size of other mainline branches can often be reduced. Other prospects for reduction are sections of mainline 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) can be computed by equation 7–62.

$$L_s = \frac{\Delta H}{h_{fs} - h_{fl}} \qquad \text{(eq. 7–62)}$$

where:
L_s = required length of smaller diameter pipe, ft (m)
ΔH = desired pressure head increase between two points, ft (m)
h_{fs} = head loss gradient of the smaller pipe, ft/ft (m/m)
h_{fl} = head loss gradient of the large pipe, ft/ft (m/m)

(g) Lateral line design

This section presents the procedures for determining lateral characteristics, such as flow rate and inlet pressure, location, and spacing of the manifolds, that in effect set the lateral lengths and estimated differences in pressure within laterals.

(1) 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 7–86 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) can be computed by equation 7–63.

$$q_L = \frac{l}{S_e} \times \frac{q_a}{60} = \frac{n_e q_a}{60} \qquad \text{(eq. 7–63)}$$

where:

q_L = lateral flow rate, gal/min (L/m)
l = length of lateral, ft (m)
S_e = spacing of emitters on the lateral, ft (m)
n_e = number of emitters along the lateral
q_a = average emitter flow rate, gal/h (L/h)

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 measured from the downstream end of the lateral. 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 so that only about a fourth of the total loss takes place between the average emitters and the end.

The inlet pressure head (h_i) that will give h_a for a pair of constant-diameter laterals with $L = S_m$ laid on a uniform slope can be computed by equations 7–64a and 7–64b.

$$h_l = h_a + 0.75 h_{fp} \left[z^K + (1-z)^K \right] - \left(\frac{\Delta E}{2} \right)(2z-1) \qquad \text{(eq. 7–64a)}$$

where:

h_l = lateral inlet pressure, ft (m)
K = 3.852 for Hazen-Williams equation and 3.75 for Keller equation
h_{fP} = friction loss in a lateral with length L, ft (m)
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)
ΔE = absolute difference in elevation between the two ends of the pair of laterals, ft (m)

For level fields this reduces to:

$$h_l = h_a + 0.75 h_{fp} (0.5)^K = h_a + 0.11 h_{fp} \qquad \text{(eq. 7–64b)}$$

where:

K = 2.852 for Hazen-Williams equation and 2.75 for Keller equation

For a single nonpaired constant-diameter lateral laid on uniform slopes, h_l can be computed by equation 7–64c,

$$h_l = h_a + \frac{3h_f}{4} + \frac{\Delta El}{2} \qquad \text{(eq. 7–64c)}$$

and the pressure head at the closed end of the lateral (h_c) can be computed by equation 7–65a or 7–65b.

$$h_c = h_a - \left(\frac{h_f}{4} + \frac{\Delta El}{2} \right) \qquad \text{(eq. 7–65a)}$$

$$h_c = h_l - \left(h_f + \Delta El \right) \qquad \text{(eq. 7–65b)}$$

where:

h_c = pressure head at the closed end of the lateral, ft (m)
h_a = average emitter pressure head, ft (m)
h_l = lateral inlet pressure head, ft (m)
h_f = head loss from pipe friction, ft (m)
ΔEl = change in elevation (+ for laterals running uphill from the inlet and – for laterals running downhill, ft (m))

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 7–64c would be changed to $h_f/2$. It is impractical to use more than two pipe sizes; therefore, when calculating h_f for a tapered lateral, replace 3h/4 with 2h/3 in equation 7–64c. When computing h_c by equation 7–65a, 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 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 7–47 (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 the discharges from all outlets are equal, and no water flows beyond the last outlet of the pipe section being considered. For further details on design of multioutlet pipeline, see NEH623.0711(h).

(2) Location and spacing of manifolds

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 3% slope restriction does not apply if PC and PC–CNL dripper lines are contemplated). 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 centerline (again, the slope restriction does not apply if PC and PC–CNL dripper lines are contemplated and the lateral pressure is maintained within the range of pressure compensation). 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 (Δh) can be limited to half of the allowable subunit pressure head variations ($0.5\ \Delta H_s$) where the manifold plus attached laterals make up a subunit. The Δh 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).

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. The procedure is as follows:

Step 1: Inspect the field layout, and select a reasonable S_m in accordance with the criteria listed.

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 equals the pressure head difference along the lateral (Δh), i.e., the field is level, and compare the latter with 0.5 times the allowable subunit pressure head variation (Δh_s) (eq. 7–41). If Δh is much larger than $0.5\ \Delta h_s$, 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 7–66a, which is a rearrangement of equation 7–53.

$$(h_f)_b = (h_f)_a \left(\frac{L_b}{L_a}\right)^K \qquad \text{(eq. 7–66a)}$$

where:

K	= 2.852 for Hazen-Williams equation and 2.75 for Keller equation
L_a and L_b	= original and new lateral pipe length, ft (m)
$(h_f)_a$ and $(h_f)_b$	= original and new lateral pipe friction losses, ft (m)

Conversely, the length of lateral (L_b) that will give any desired $(h_f)_b$ can be computed by equation 7–66b.

$$L_b \cong L_a \left[\frac{(h_f)_b}{(h_f)_a} \right]^k \qquad \text{(eq. 7–66b)}$$

where:
K = 0.35 for the Hazen-Williams equation and 0.36 for the Keller equation

Location of manifolds—On level fields, laterals should extend an equal length (1) to either side of the manifolds so that 1 equals 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 7–50. The location of the manifold that will give the same minimum and maximum pressures in the uphill and downhill laterals can be determined.

Figure 7–93 shows the dimensionless terms used in the following computation:

Step 1: Determine h_f 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 absolute elevation difference in the lateral, $\Delta E < h_f$. If $\Delta E > h_f$, then Y = 1. This is the ratio of x/L where the friction curve is tangent to the ground, figure 7–93.

$$Y = \left(F \frac{\Delta E}{h_f} \right)^K \qquad \text{(eq. 7–67)}$$

where:
Y = ratio of x/L where the friction curve is tangent to the ground
ΔE = absolute elevation difference, ft (m)
F = multiple outlet factor
h_f = lateral friction loss, ft (m)
K = 0.54 for the Hazen-Williams equation and 0.57 for the Keller equation

Step 3: Determine the optimum x/L (z) that satisfies equation 7–68. Keller and Bliesner (1990).

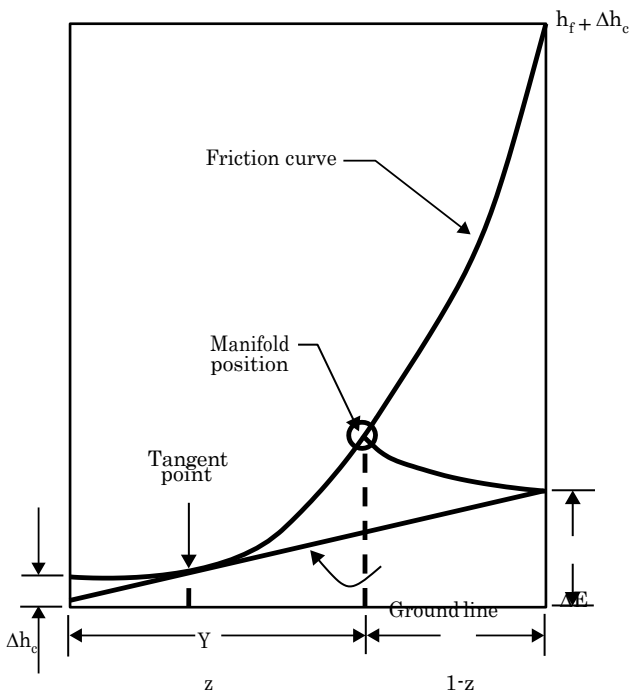
$$\frac{\Delta E}{h_f} - 0.36 \left[\frac{\Delta E}{h_f} \right]^{K1} = (z)^{K2} - (1-z)^{K2} \qquad \text{(eq. 7–68)}$$

where:
z = optimum manifold location that will give the same minimum and maximum pressures in the uphill and downhill laterals
K1 = 1.54 for the Hazen-Williams equation and 1.57 for the Keller equation
K2 = 2.75 for the Hazen-Williams equation and 2.852 for the Keller equation

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. Table 7–26 provides another method of estimating the optimum manifold position without an iterative procedure and still provides a reasonably accurate solution (Keller and Bliesner 2000).

Step 4: For laterals on relatively mild slopes, the maximum pressure head variation Δh along a pair of laterals can now be determined from the x/L or z value that represents the actual manifold location selected by using equation 7–69 (Keller and Bliesner 1990).

Figure 7–93 Sketch showing relationship between manifold position and lateral hydraulics for a paired lateral



$$\Delta h = \Delta E(1-z) + h_f(1-z)^K \qquad \text{(eq. 7–69)}$$

where:
K = 2.852 for Hazen-Williams equation and 2.75 for Keller equation

For steep slopes, the maximum Δh may occur at the closed end of the lateral. To check for this possibility, determine the difference (Δh_c) between the downstream-end and minimum pressure heads by equation 7–70 (Keller and Bliesner 2000).

$$\Delta h_c = \Delta E(Y) - h_f(Y)^K \qquad \text{(eq. 7–70)}$$

where:
K = 2.852 for Hazen-Williams equation and 2.75 for Keller equation

(3) Pressure difference

The pressure head difference (Δh) along the laterals must be known for estimating the final emission uniformity (EU) of the system. As mentioned before, Δh should be about 0.5 times the allowable subunit pressure head variation (ΔH_s) or less. Methods for computing Δh are stated in step 4 for manifold positioning. However, for some designs, the manifold placement is dictated by other considerations and Δh must be determined by some other means.

Table 7–26 Best manifold position z on sloping field. Hoses go uphill and downhill from manifold expressed as a ratio of the downhill lateral to L

$\frac{\Delta E}{h_f}$	z	$\frac{\Delta E}{h_f}$	z
0.0	0.5	1.0	0.85
0.1	0.56	1.2	0.89
0.2	0.60	1.4	0.92
0.3	0.65	1.6	0.94
0.4	0.69	1.8	0.96
0.5	0.72	2.0	0.98
0.6	0.75	2.2	0.99
0.7	0.78	2.4	1.00
0.8	0.81	2.6	1.00
0.9	0.83	2.75	1.00

For laterals on downhill slopes of less than 0.3 percent, level ground, or uphill slopes, Δh can be assumed equal to the lateral inlet pressure head (h_l) minus the pressure head at the closed end (h_c) and equations 7–64 and 7–65 can be used to determine h_l and h_c. This works for a single or paired lateral. For steeper downhill laterals, equations 7–64 and 7–65 are still valid as long as the slope is fairly uniform. However, a different procedure must be used to estimate Δh because the highest and lowest pressures will no longer be at h_l and h_c. This is the situation for both a single or a paired lateral. A more detail description of the subject can be found in the book written by Keller and Bliesner, Sprinkle and Trickle Irrigation. This is apparent in figure 7–93 where the pressure is lowest at the manifold position (z) = the tangent location (Y).

Use the following steps to compute Δh for laterals on slopes steeper than 3 percent.

Steps 1 through 3: Follow steps 1 through 3 above for determining the position for the manifold on sloping fields, except that the equivalent friction loss should be determined for the length of lateral under study rather than for the S_m.

Step 4: For relatively mild slopes, the maximum difference in pressure head (Δh) along the lateral can be computed by equation 7–71.

$$\Delta h = \Delta h_c = \Delta E\, h_f \qquad \text{(eq. 7–71)}$$

where:
h_f = friction loss found in step 1

Equation 7–71 is the same as equation 7–70 with z = 1 because the manifold would be located at z = 1 in figure 7–93, which is a dimensionless sketch showing terms in the numerical solution of optimum position for manifold.

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 (Δh_c) by equation 7–70.

(h) Manifold design

This section presents the procedures for determining the characteristics of a manifold, flow rate, and pipe sizes to keep within the desired pressure head dif-

ferential 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 mainline should be positioned so that starting from a common mainline connection the minimum pressures along the pair of manifolds (one to either side of the mainline) 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 mainline layout is a compromise between field geometry and manifold hydraulics. The allowable manifold pressure head variation may be computed by equation 7–72.

$$\left(\Delta H_{m_a}\right) = \Delta H_s - \Delta h' \qquad \text{(eq. 7–72)}$$

where:

(ΔH_{m_a}) = allowable manifold pressure head variation

ΔH_s = the allowable subunit pressure variation, ft (m)

$\Delta h'$ = the greater of Δh or Δh_l, the lateral line pressure variation, ft (m)

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.

(1) 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 half that of the largest pipe. The velocity should be limited to about 7 feet per second (2.13 m/s) in manifolds. This is higher than the 5 feet per second (1.52 m/s) used for mainlines 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 7–86 are a pair. If only one manifold is connected at an inlet point, as in figure 7–50, the design is termed a single-manifold configuration.

The length of a pair of manifolds (L,) can be computed by equation 7–73.

$$L_p = \left[\left(n_r\right)_p - 1\right] S_r \qquad \text{(eq. 7–73)}$$

where:

L_p = length of a pair of manifolds, ft (m)

$(n_r)_p$ = number of row (or lateral) spacings served from a common inlet point

S_r = row spacing, ft (m)

The length of a single manifold (L_m) is usually equal to that computed by equation 7–74.

$$L_m = \left(n_r - \frac{1}{2}\right) S_r \qquad \text{(eq. 7–74)}$$

where:

L_m = length of a single manifold, ft (m)

n_r = number of row (or lateral) spacings served by the manifold

S_r = row spacing, ft (m)

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, and topographic features such as drains, structures, or existing facilities often dictate the location of mainlines 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 the procedure outlined in NEH623.0712(a)(2), 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 $[(\Delta H_m)_a]$.

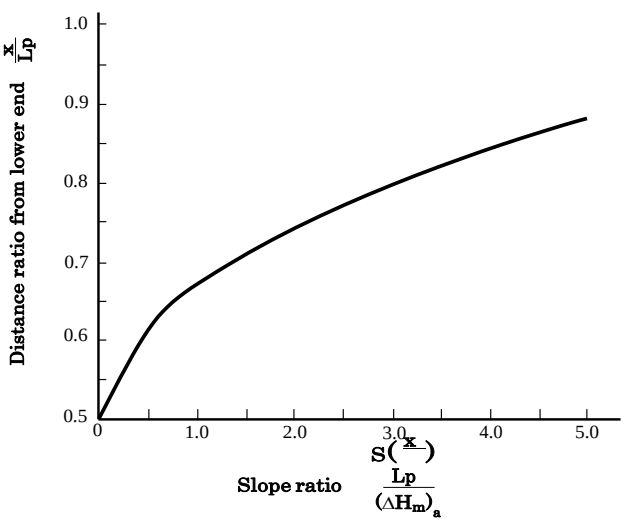
The inlet location that will balance the minimum uphill and downhill pressures is not precise for tapered manifolds because it depends on the selection of pipe sizes and lengths. Figure 7–94 was developed as a guide to selecting the inlet location for tapered manifolds. The use of this figure greatly 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.

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.

Example

Given: $(\Delta H_m)_a = 0.5$ ft for a pair of manifolds with $L_p = 1{,}000$ ft and S = 1%.

Figure 7–94 Graph for selecting location of inlet to a pair of tapered manifolds on a slope



Solution: Using figure 7–95, the manifold inlet location can be found as follows:

$$\text{slope ratio} = \frac{\frac{S}{100}(Lp)}{(\Delta Hm)_a} = \frac{\frac{1}{100}(1000)}{5} = 2$$

From figure 7–95, the downhill portion of the paired manifold is equal to 0.75 × L_p; therefore,
L_m = 750 feet for the downhill manifold, and
L_m = 250 feet for the uphill manifold

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.

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 inlet pressure head (H_m) for subunits with single pipe size laterals can be computed by equations 7–75a and 7–75b.

$$H_m = h_l + \Delta Hm' \qquad \text{(eq. 7–75a)}$$

where:
H_m = manifold inlet pressure, ft (m)
h_l = lateral inlet pressure that will give the average pressure head (h_a), ft (m)
$\Delta H_m'$ = difference between the manifold inlet pressure and h_l, ft (m). It can be estimated by equation 7–76

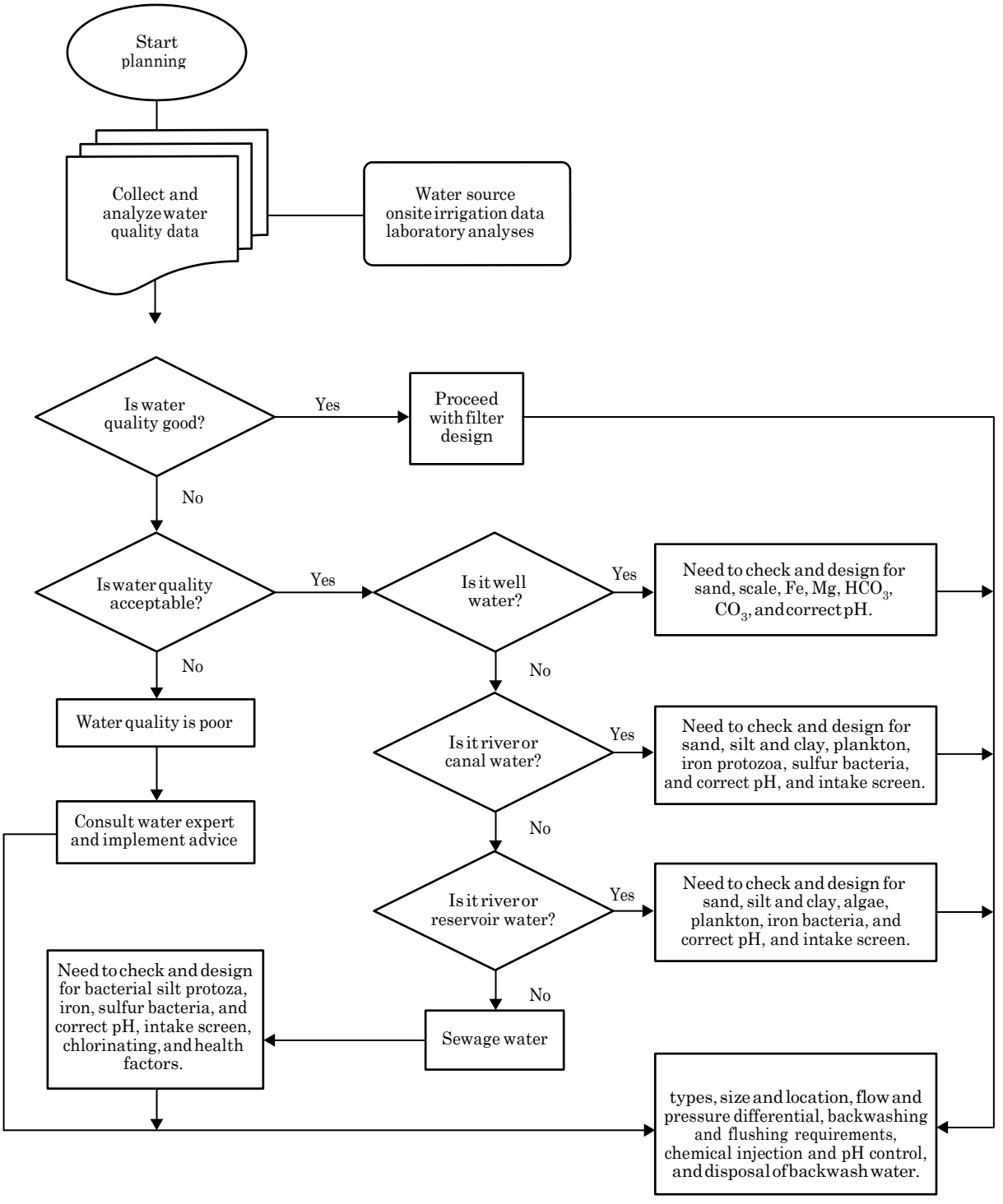
For laterals with one tubing diameter on uniform slopes, h_l can be determined either by equation 7–64a, b or c.

For tapered laterals:

$$H_m = h_a + \Delta h' + \Delta H_m' \qquad \text{(eq. 7–75b)}$$

where:
H_m = manifold inlet pressure, ft (m)
h_a = average emitter operating pressure, ft (m)
$\Delta h'$ = difference between the lateral inlet pressure and h_a, ft (m). For tapered laterals, $\Delta h'$ should be estimated graphically

Figure 7–95 Flow chart for the selection and design of a filtration system



$\Delta H_m'$ = difference between the manifold inlet pressure and h_1, ft (m). It can be estimated by equation 7–76

$$\Delta Hm' = MH_f + 0.5 \times \Delta E1 \qquad \text{(eq. 7–76)}$$

where:
M = 0.75 for manifolds with one pipe size
M = 0.6 for manifolds with two pipe sizes
M = 0.5 for manifolds with three or more pipe sizes

(2) 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 7–77.

$$(H_f)_2 = \left(\frac{L_2}{L_1}\right)\frac{(F_s)_2}{(F_s)_1}\left(\frac{q_2}{q_1}\right)^{1.8}(H_f)_1 \qquad \text{(eq. 7–77)}$$

where:
$(H_f)_2$ = estimate of the pressure head loss from pipe friction for the manifold, ft (m)
$(H_f)_1$ = pressure head loss from pipe friction for the original manifold, ft (m)
L_1 = length of pipe in the original manifold, ft (m)
L_2 = length of pipe in the manifold for which $(H_f)_2$ is being estimated, ft (m)
$(F_s)_1$ = 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, gal/min (L/min)
q_2 = flow rate in the manifold for which $(H_f)_2$ is being estimated, gal/min (L/min)

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.

(i) Filter selection

The main purpose of filtration is to keep mainlines, submains, laterals, and emitters clean and working properly. The most common types of filters, their functions, and recommended uses were outlined in table 7–10. Before embarking on design of the filtration system, questions regarding water source, water quality, flow rate, type of MI system, and fertigation chemistry need to be considered. In the absence of manufacturer data or recommendations, it is recommended that filtration systems be designed to remove solids equal to or larger than one-tenth the emitter opening diameter because particles may group together and bridge the emitter openings. The flowchart in figure 7–95 should be followed to guide selection and design of the filtration system. The filtration system selected should be sized to filter total system flow rate.

This section includes procedures for determining selection parameters for a sand media filtration system, such as flux, flow rate, tank size, and number of tanks, needed to give the desired average contaminant removal.

The flux (flow capacity per unit area) of a media filter defines the velocity of the flow of the water through the filtering media (Sagi et al. 1995). The filter should be sized for extreme contaminant loads and diversity so that it can be flushed as needed and still deliver the flow rate needed for peak crop ET. Table 7–27 gives flow rates through sand media filters for various fluxes and tank diameters. For DI and SDI, a typical design flux is about 20 to 25 gallons per minute per square foot (L/min/m^2). If space is available, additional parallel tanks can be added to a media filter system, if needed to increase system delivery capacity.

Knowing the desired flux, the tank diameter and the irrigated block flow capacity, the number of tanks required N_t can be calculated:

$$N_t = \frac{Q_s}{t_f} \qquad \text{(eq. 7–78)}$$

where:
N_t = minimum number of tanks
Q_s = flow capacity for the largest block, gal/min (L/s)
t_f = specific tank flow rate for a given diameter and flux, gal/min (L/s)

A flux of 25 gallons per minute per square foot (16.9 L/s/m^2) is usually recommended, although higher fluxes have been used successfully. In certain cases where

surface water quality may decrease gradually during the season, it may be recommended to use a lower flux (known as de-rating the filter), keeping in mind that small diameter tanks require less backflush water.

The flow rate across the sand medium is an important consideration in filter selection. Figure 7–25 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. Filter sand is graded by its effective size and its uniformity coefficient (table 7–28).

The mean effective sand size is the size opening that will pass 10 percent of a representative sand sample and is given in millimeters. A mean effective size of 1.50 means that 10 percent of the sample is finer than 1.50 millimeters.

The uniformity coefficient is the ratio of the size opening that will just pass 60 percent of a representative sample of sand divided by that opening that will pass just 10 percent of the same sample. A uniformity coefficient of 1.5 or less is good for irrigation filter sand grades (Boswell 1984).

The American Society of Agricultural and Biological Engineers (ASABE) Standard S539 (ASABE 2003) outlines testing and performance reporting for media filters for irrigation and may be used when no other standard is available.

The backwashing of media filters is described in detail in NEH623.0708. The filtration system must be sized properly to provide the required backwash flow rate while continuing to supply sufficient filtered water for the irrigation system. Table 7–29 shows the backwash flow rates needed to sustain adequate filter backwashing while irrigating. These data show that horizontal tanks require a lower backwashing flow rate than the vertical tanks, which may be an important selection criteria when the flow rate is a critical factor.

Table 7–27 Typical flow rates through media filters for various fluxes and tank diameters (adapted from Haman, Smajstrla, and Zazueta 1994)

FLUX–gal/min/ft² (L/s/m²)	Tank diameter 18 in gal/min/tank (460 mm L/s/tank)	Tank diameter 24 in gal/min/tank (610 mm L/s/tank)	Tank diameter 30 in gal/min/tank (760 mm L/s/tank)	Tank diameter 36 in gal/min/tank (910 mm L/s/tank)	Tank diameter 48 in gal/min/tank (1220 mm L/s/tank)
15 (10.2)	27 (1.7)	47 (3.0)	74 (4.7)	106 (6.7)	189 (11.9)
20 (13.6)	35 (2.2)	53 (3.3)	98 (6.2)	141 (8.9)	251 (15.8)
25 (16.9)	44(2.8)	79 (5.0)	123 (7.8)	177(11.2)	314 (19.8)
30 (20.3)	53 (3.3)	94 (5.9)	147(9.3)	212 (13.4)	377 (23.8)

Table 7–28 Characteristics of commercially available grades of media sand (after Boswell 1984)

Sand media number	Mean effective sand size (mm)	Uniformity coefficient	Media type	Filtration quality (mesh)
Number 8	1.50	1.47	Crushed granite	100–140
Number 11	0.78	1.54	Crushed granite	140–200
Number 16	0.66	1.51	Crushed silica	140–200
Number 20	0.46	1.42	Crushed silica	200–250

Table 7–29 Minimum backwash flow rates, gallons/minute/tank (L/min/tank) by type of media needed to sustain adequate (a) vertical tank and (b) horizontal filter backwashing while irrigating

(a) Backwash flow rate per vertical tanks, gallons per minute (L/s)

Media type	Tank diameter 18 in (460mm) gal/min (l/s)	Tank diameter 24 in (610mm) gal/min (l/s)	Tank diameter 30 in (760mm) gal/min (l/s)	Tank diameter 36 in (910mm) gal/min (l/s)	Tank diameter 48 in (1220mm) gal/min (l/s)
Number 8	51 (3.2)	91 (5.7)	141 (8.9)	201 (12.7)	360 (22.7)
Number 11	26 (1.6)	48 (3.0)	74 (4.7)	105 (6.6)	188 (11.9)
Number 16	32 (2.0)	57(3.6)	89 (5.6)	126 (7.9)	225 (14.2)
Number 20	26 (1.6)	48 (3.0)	74 (4.7)	105 (6.6)	188 (11.9)

(b) Backwash flow rate per horizontal tanks

Media type	Tank diameter 18 in (460mm) gal/min (l/s)	Tank diameter 24 in (610mm) gal/min (l/s)	Tank diameter 30 in (760mm) gal/min (l/s)	Tank diameter 36 in (910mm) gal/min (l/s)	Tank diameter 48 in (1220mm) gal/min (l/s)
Number 8	43 (2.7)	57 (3.6)	71 (4.5)	86 (5.4)	114 (7.2)
Number 11	23 (1.5)	30 (1.9)	38 (2.4)	45 (2.8)	60 (3.8)
Number 16	28 (1.8)	36 (2.3)	46 (2.9)	54 (3.4)	72 (4.5)
Number 20	23 (1.5)	30 (1.9)	38 (2.4)	45 (2.8)	60 (3.8)

(j) Flushing manifold and minimum flushing velocity

Flushing of MI systems is required to control sediment buildup in the mains, submains, manifolds, and laterals and to prevent emitter clogging. The ASABE Standard 405.1, Design and Installation of MI Systems (ASABE 2003), recommends flushing the system weekly and using a minimum flushing velocity of 1 foot per second (0.3 m/s). Filtration should be effective enough so that flushing events are not required more frequently than once weekly.

There are several ways to flush MI systems either manually or automatically:

- Each lateral can be equipped with an automatic pressure-dependent flush valve that opens when the line pressure drops below a certain threshold. In this case, flushing occurs at the beginning and at the end of an irrigation cycle and will require a significant increase in pump flow rate.
- Each lateral can also be opened manually by the irrigator, one or more lateral at a time.
- Flushing manifolds can also be designed to accommodate several laterals and be operated either manually or automatically.

This section addresses the design criteria of flushing manifolds. Figure 7–96 shows a cross section of a flushing manifold used with SDI systems. Friction losses due to connectors, depth of the manifold, and flush valve should be accounted for in the head loss calculations. The flushing riser and valve assembly can be located either at one end of the manifold, in the center of the manifold when the manifold is level or anywhere along the manifold installed on a slope to balance the pressure.

Drip lateral connections, flushing manifold, and valve should be sized to minimize head loss and maintain flushing pressure during flushing at about 3 psi (21 kPa as shown in fig. 7–89). A flushing manifold with a cross-sectional area of 25 percent or more of the sum of all the cross-sectional area of the drip lateral connections is sufficient to maintain a flushing veloc-

ity of 1 foot per second (0.3 m/s) (Lamm and Camp, *in* press). Assuming a flushing velocity of 1 foot per second (0.3 m/s), Lamm and Camp developed a simple equation for calculating the flushing manifold diameter.

$$D_f = 0.5 D_d \sqrt{N_d} \qquad \text{(eq. 7–79)}$$

where:

D_f = the flushing line diameter, rounded up to the next available nominal pipe size, in (mm)

D_d = the dripper line diameter, in (mm)

N_d = number of dripper lines flowing in that branch of the flushing line towards the flush valve

For cases where the flushing manifold is level, the flushing riser will be located in the middle of the manifold, and an equal number of lateral lines will be flowing into each branch of the manifold. The friction loss for a level-grade flushing manifold can be calculated by equation 7–52.

$$h_f = F\, h_{f\,no\,outlets} \qquad \text{(eq. 7–52)}$$

where:

h_f = head loss from pipe friction, ft (m)

F = reduction coefficient to compensate for the discharge along the pipe (from table 7–24)

$h_{f\,no\,outlets}$ = friction loss of a pipe with only one outlet

For the complete flush valve assembly shown in figure 7–96, Lamm and Camp (2007) suggest that the flush valve size D_v can be calculated using equation 7–80:

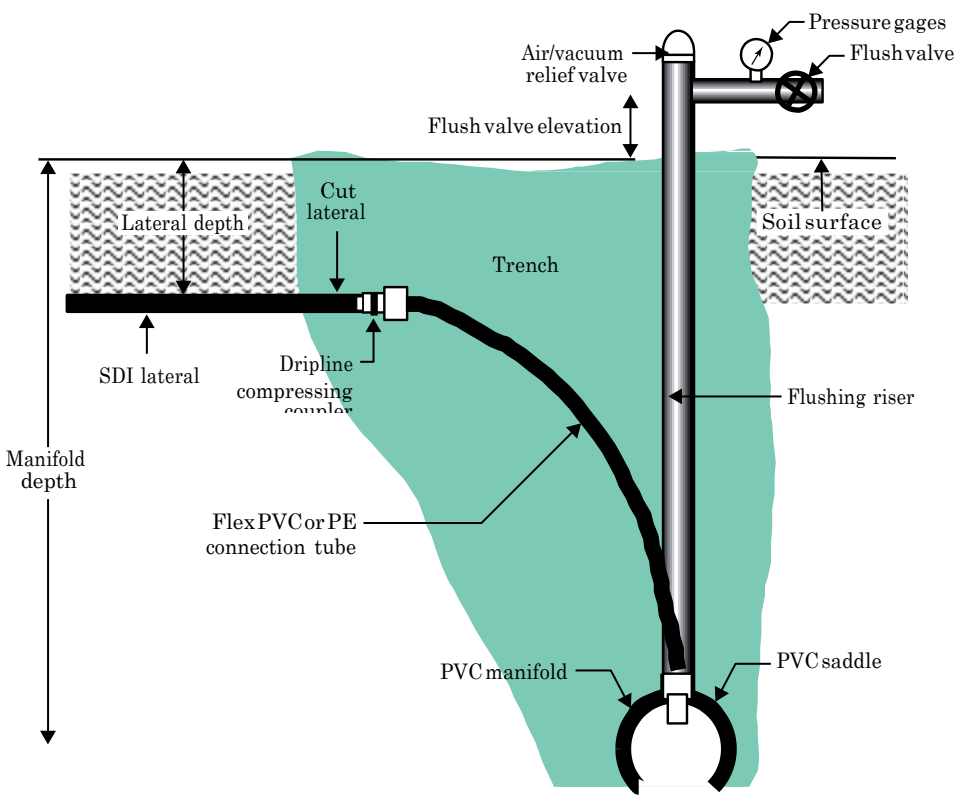
$$D_v = K_v \frac{\sqrt{Q_v}}{(P_v)^{0.25}} \qquad \text{(eq. 7–80)}$$

where:

D_v = flushing valve size, in (mm)

K_v = 0.22 for English units (35.7 metric units) for a branched flush valve (T-manifold) and 0.20

Figure 7–96 Suggested flushing manifold design for a SDI system (adapted from Phene 1999)



(33.4) for the nonbranched (single-sided manifold) flush valve

Q_v = the total flow rate, gal/min, (L/s), through the flush valve at a flushing velocity of 1 foot per second (0.3 m/s)

P_v = the allowable pressure loss, psi, (kPa), through the flush valve assembly during flushing. P_v 0.5 psi

After equation 7–80 has been used to size the flush valve, the actual pressure loss can be calculated by rearranging equation 7–80 (Lamm and Camp 2007).

The design methods outlined in NEH623.0711(h), Manifold design, can also be used to design more complicated flushing manifolds using multiple size pipes or other configurations to reduce flushline friction loss.

623.0712 Sample designs for microirrigation

The following sample designs illustrate some of the procedures of this handbook.

(a) Surface drip system for deciduous almond orchard

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 drip irrigation design data sheet (fig. 7–97) and the orchard layout map (fig. 7–98). In addition to illustrating the general process for designing a drip irrigation system, the example emphasizes the following procedures:

Step 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).

Step 2: Determining ΔH_s, the allowable variation in pressure head that will produce the desired uniformity of emission.

Step 3: Positioning the manifolds and designing the laterals (with both graphical and numerical solutions) for sloping rows.

Step 4: Designing the manifold and selecting economical pipe sizes for both manifolds and main lines.

Step 5: Computing system capacity and total dynamic operating-head requirements.

Step 6: Determining inlet flow and pressure required to provide adequate flushing velocity.

(1) Design factors

Before designing the hydraulic network, the designer must determine the type of emitter, the emitter flow characteristics and spacing (S_e), average emitter discharge (q_a), average emitter pressure head (h_a), allowable head variation (ΔH_s), and hours of operation per season (O_t). The type of emitter used will greatly affect the design and economics. For example, the use of a PC emitter with a zero or near zero exponent (x) will significantly simplify the design, but may increase the

Figure 7–97 Drip system data for a deciduous almond orchard in the Central Valley of California

I Project Name—Happy Green Farm

II Land and Water Resources

a	Field no.	#1
b	Field area, acre (ha) A	115.68
c	Average annual effective rainfall, in (mm), R_e	3.7
d	Residual stored soil moisture from off-season precipitation, in (mm), W_s	0
e	Water supply, gal/min (L/s)	1000
f	Water storage, acre-ft (ha-m)	-----
g	Water quality (dS/m) EC_w	1.4
h	Water quality classification	Relatively high salinity (fig. 7–15)

III Soil and Crop

a	Soil texture	Silt loam
b	Available water-holding capacity, in/ft (mm/m), WHC	1.8
c	Soil depth, ft (m)	10
d	Soil limitations	None
e	Management-allowed deficiency (%), MAD	30
f	Crop	Almond
g	Plant spacing, ft × ft (m × m), $S_e \times S_r$	24 × 24
h	Plant root depth, ft (m), RZD	6
i	Average daily peak ET_c rate for the month of greatest overall water use, in/d (mm/d), ET_c	0.30
j	Season total crop consumptive-use rate, in (mm), ET_s	36.74
k	Leaching requirement (ratio), LR	0

IV Emitter

a	Type	Vortex
b	Outlets per emitter	1
c	Pressure head, lb/in^2 (kPa), h	15.0
d	Rated discharge@h, gal/h (L/h), q	1.0
e	Discharge exponent, x	0.42
f	Coefficient of variability, CV	0.07
g	Discharge coefficient, k_d	0.32
h	Connection loss equivalent, ft (m), f_e	0.4
i	Spacing between emitters along a lateral, ft (m), S_e	6.0
j	Emitter orifice diameter, in (mm)	0.02

Figure 7–98 Orchard layout showing pump, mainline, and submains

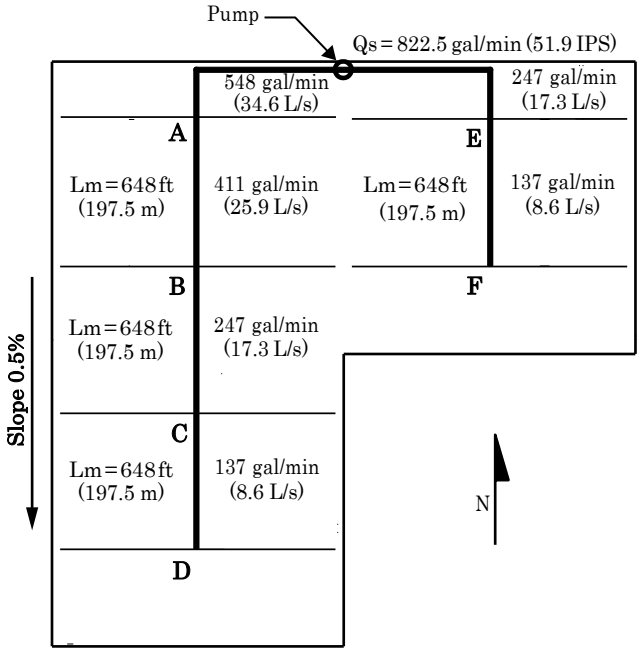
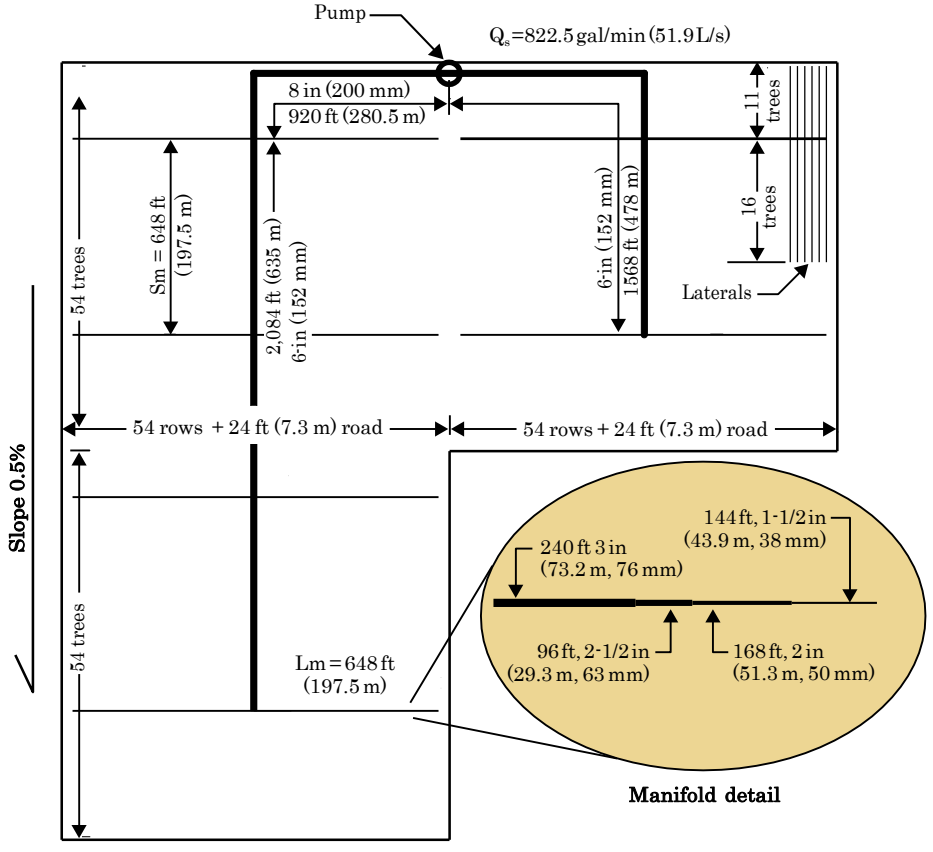


Figure 7–99 Orchard layout with sample design for a drip irrigation system. (Lateral lines are 0.58-in (14.7 mm) polyethylene (PE), manifolds are SDR 26 polyvinyl chloride (PVC), and mainlines are SDR (41 PVC)



cost of the system. The final layout, emitter, and spacing selected for this example is shown in figure 7–99.

The steps for developing these factors are outlined in the MI design factors sheet (fig. 7–100). 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 drip irrigation systems in the same area have shown that the wetted diameter produced by 1.0 gallon per hour (3.785 L/h) emitters is between 8 and 9 feet (2.432 and 2.736 m). For a continuous wetted strip, the spacing between emitters in the row should not exceed 80 percent of the wetted diameter, and emitter spacing should be selected such that each plant will receive a whole number of emitters. Therefore, for the 24-foot (7.296 m) tree spacing, a uniform S_e of 6.0 feet (1.824 m) was selected. Table 7–14 can help predict the areas wetted by an emitter; however, field test data and observations of existing systems are preferable.

Percent area wetted (P_w)—Using equation 7–8 with the following input data we calculate P_w.

S_e = 6.0 ft (1.824 m)
S_w = 8.5 ft (2.584 m) (field data)
S_p = 24 ft (7.296 m)
S_r = 24 ft (7.296 m)
e = S_p/S_e = 4.0

$$P_w = \frac{eS_eS_w}{S_pS_r} \times 100 \qquad \text{(eq. 7–8)}$$

$$P_w = \left\{\frac{(4.0 \times 6 \times 8.5)}{(24 \times 24)}\right\} \times 100$$

$$P_w = 35.42\%$$

Maximum net depth of application (F_{mn})—Using equation 7–11 with the following input data we calculate F_{mn}.

MAD = 30%
WHC = 1.8 in/ft (150 mm/m)
RZD = 6.0 ft (1.824 m)
Pw = 35.42%

$$F_{mn} = (MAD)(WHC)(RZD)(P_w) \qquad \text{(eq. 7–11)}$$

$$F_{mn} = (0.30)(1.8)(6.0)(0.3542) = 1.15 \text{ in}$$

Average peak daily evapotranspiration rate (ET_c)—Equation 7–12a can be used to calculate the average daily evapotranspiration using the calculated ET_o:

$$ET_c = K_c \times ET_o = 1.25 \times 0.24 = 0.30 \text{ in/d} \qquad \text{(eq. 7–12a)}$$

where:
ET_o = average daily reference evapotranspiration (grass) for month of greatest use from eq. 7–12a = 0.24 in/d (6.1 mm/d)
K_c = crop coefficient for month of greatest ET_c is equal to 1.25

Seasonal evapotranspiration rate (ET_s)—The seasonal evapotranspiration rate (ET_s), inches per year (mm/yr), can be computed by summing up ET_c in equation 7–12b for the whole cropping season.

$$ET_s = \sum_{\text{Planting}}^{\text{Harvest}} K_c ET_o \qquad \text{(eq. 7–12b)}$$

$$ET_s = \sum_{\text{Planting}}^{\text{Harvest}} K_c ET_o$$

$$ET_s \approx 36.74 \text{ in/yr (933.2 mm/yr)} \qquad \text{(eq. 7–12c)}$$

Maximum allowable irrigation interval (days) (I_f)—Rearranging equation 7–13 with the following input data, we calculate I_f for the maximum net application.

$$F_n = ET_c I_{fc}$$

$$I_f = \frac{F_n}{ET_c}$$

$$I_f = \frac{1.15}{0.30} = 3.8 \text{ d}$$

Design irrigation interval (days) (I_{fd})—In developing the design factors, 1 day will be used because the actual interval used is a management decision and does not affect the design hydraulics.

F_n = 0.30 in
ET_c = 0.30 in/d
(29.1 m)

(eq. 7–11a)

$$I_{fd} = \frac{F_{nm}}{ET_c}$$

Figure 7–100 Drip-system design factors for a deciduous almond orchard in the Central Valley of California

I Project Name—Happy Green Farm

II Trial Design

a	Emission point layout	Straight line
b	Emitter spacing, ft × ft (m × m) $S_e \times S_l$	6 × 24
c	Emission points per plant, e´	4
d	Percent area wetted, %. P_w	35.42
e	Maximum net depth of application, in (mm), F_{mn}	1.15
f	Average peak-of-application daily ET_c rate, in/d (mm/d), ET_c	0.30
g	Maximum allowable irrigation interval, day, I_f	1.0
h	Design Irrigation interval, day, I_f	1.0
i	Net depth of application, in (mm), Fn	0.30
j	Design emission uniformity, % EU	90
k	Leaching requirement ratio (high frequency) LR	0.006
l	Gross water application, in (mm) F_g	0.33
m	Gross volume of water required/plant/day, gal/d (L/d) F(gp/d)	118.4
n	Time of application, hr/d, T_a	29.6
o	Electrical conductivity of water, dS/m EC_w	1.4

III Final design

a	Time of application, hr/d, T_a	21.00
b	Design irrigation interval, d, I_f	1.0
c	Gross water application, in (mm) F_g	0.33
d	Average emitter discharge, gal/h (L/h), q_a	1.41
e	Average emitter pressure head, ft (m), h_a	78.8
f	Allowable pressure head variation, ft (m), Δhs	25.69
g	Emitter spacing, ft × ft (m × m), $S_e \times S_l$	6 × 24
h	Percent area wetted, % P_w	35.42
i	Number of stations, N	1
j	Total system capacity, gal/min, (L/min), Q_s	823
k	Seasonal irrigation efficiency, %, E_s	90
l	Gross seasonal volume, acre/ft (m^3) V_i	353.5
m	Seasonal operating time, hr, O_t	2,384
n	Total dynamic head, ft (m), TDH	138.2
o	Final emission uniformity, %, EU	91
p	Net application rate, in/h (mm/h), I_n	0.0112
q	Maximum net daily application rate, in/d (mm/d), F_{mn}	0.27

$$I_{fd} = \frac{0.30}{0.30}$$
$$= 1 \text{ d}$$

Net depth of application—The net depth of application (F_n), inches, for DI and SDI systems is the net amount of moisture to be replaced at each irrigation to meet the ET_c 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 7–13.

$$F_n = ET_c I_{fc} \qquad \text{(eq. 7–13)}$$

$$F_n = ET_c \times 1.0$$
$$= 0.30 \text{ in } (7.6 \text{ mm})$$

where:

ET_c = average peak daily evapotranspiration rate for the mature crop, in/d

I_f = design irrigation interval, days, for DI and SDI, $I_f = 1$

Emission uniformity (EU)—An emission uniformity of 90 percent is a practical design objective for drip systems on relatively uniform topography.

Average peak daily transpiration ratio (T_r)—Because the crop is deep rooted and the soil is medium texture, T_r equals 1.00 as described in gross water application under soil-plant-water considerations.

Leaching requirement ratio (Lr)—Based on ECw, leaching is not required because ECw < min. ECe (eq. 7–24).

Gross water application (F_g)—Using equation 7–15a with the following input data, we calculate F_g;

T_r = 1.00
Lr = 0.0
F_n = 0.30 in (mm)
EU = 90%

- When the unavoidable losses are greater than the leaching requirement, i.e., $T_r \geq 1/(1–Lr)$, or
- $Lr \leq 0.1$, then extra water for leaching is not required during the peak use period, and F_g should be computed by equation 7–15a.

$$F_g = \frac{(F_n T_r)}{\left(\frac{EU}{100}\right)}$$
$$= 0.33 \text{ in/d } (8.4 \text{ mm}) \qquad \text{(eq. 7–15a)}$$

Gross volume of water required per plant per day ($F_{(gp/d)}$)—Using equation 7–16 with the following input data, we calculate (F(gp/d)).

F_g = 0.33 in (8.4 mm)
S_p = 24 ft (7.3 mm)
S_r = 24 ft (7.3 mm)
I_f = 1 d

$$F_{\left(\frac{gp}{d}\right)} = 0.623\left[\frac{S_p S_r F_g}{I_f}\right]$$
$$= 0.623\left[\frac{24 \times 24 \times 0.33}{I}\right] \qquad \text{(eq. 7–16)}$$
$$= 118.42 \text{ gal/d } (448.2 \text{ L/d})$$

Time of application (T_a)—Using equation 7–37 with the following input data, we calculate (T_a);

$F_{(gp/d)}$ = 118.42 bal/d (448.2 L/d)
e = 4
q_a = 1.0 gal/h (3.785 L/h)

$$T_a = \frac{F_{\left(\frac{gp}{d}\right)}}{e(q_a)} \qquad \text{(eq. 7–37)}$$
$$= \frac{118.42}{4 \times 1.0}$$
$$= 29.6 \text{ h/d} > 21.6$$

- Adjusting q_a would bring T_a to within the allowable limits, i.e., 90 percent of 24 = 21.6 hours per day. Because T_a = 29.6 hour, one station will be used for the system, and the q_a will be increased to give 118.42 gallons per day (448.2 L/d) in 21.6 hours per day or less. (If $T_a \cong 12$ h/d, two stations can be used, and if $T_a \cong 6$ h/d, four stations can be used.)
- For added safety and convenience of operation, let T_a = 21.0 hours per day.

Average emitter discharge (q_a)—Using and rearranging equation 7–37 with the following input data calculate (q_a):

T_a = 21.0 h
$F_{(gp/d)}$ = 118.42 gal/d (448.2 L/d)
e = 4.0

The q_a that will apply the desired volume of water in T_a = 21.0 h is:

$$T_a = \frac{F_{(gp/d)}}{e(q_a)}$$

$$q_a = \frac{118.42}{4 \times 1.0} \qquad \text{(eq. 7–37)}$$

$$= 1.41 \text{ gal/h } (5.337 \text{ L/h})$$

Average emitter pressure head (h_a)—Since the emitter flow rate has been adjusted, the new average emitter pressure head (h_a) needs to be calculated. Using equation 7–38, adjust the value of h_a to what would give the required q_a.

$$h_a = \left(\frac{q_a}{k_d}\right)^{\frac{1}{x}}$$

$$= \left(\frac{1.41}{0.32}\right)^{\left(\frac{1}{0.42}\right)} \qquad \text{(eq. 7–38)}$$

$$= 34.16 \text{ lb/in}^2$$

or 78.8 ft (235.7 kPa or 24.018 m)

Allowable pressure head variation (ΔHs) (subunit)—Using equation 7–40a with the following input data, calculate (q_n):

e' = 4
CV = 0.07

q_a = 1.41 gal/h (5.337 L/h)

EU = 90%

K = 0.32
x = 0.42
h_a = 34.16 lb/in² (235.7 kPa)

- A subunit is defined as 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 objective is to limit the pressure variation within a subunit so that actual emission uniformity (EU) will equal or exceed the assumed value of EU.

$$EU = 100\left(1.0 - 1.27\frac{CV}{\sqrt{e'}}\right)\frac{q_n}{q_a} \qquad \text{(eq. 7–40a)}$$

- Rearranging equation 7–40a, the minimum permissible flow, q_n is:

$$q_n = \left[1.41 \times \left[\frac{\left(\frac{90}{100}\right)}{1.0 - \left(0.07 \times \left(\frac{1.27}{\sqrt{4}}\right)\right)}\right]\right]$$

$$= 1.33 \text{ gal/h } (5.034 \text{ L./h})$$

- The minimum permissible pressure head (h_n) that would give q_n is given by equations 7–38 and 7–44:

$$h_a = \left(\frac{q_a}{k_d}\right)^{\frac{1}{x}} \qquad \text{(eq. 7–38)}$$

$$q_n = q_a\left(\frac{h_n}{h_a}\right)^x \qquad \text{(eq. 7–44)}$$

$$\frac{q_n}{q_a} = \left(\frac{h_n}{h_a}\right)^x$$

or

$$h_n = h_a\left(\frac{q_n}{q_a}\right)^{\frac{1}{x}}$$

$$h_n = \frac{\left(\frac{q_a}{k_d}\right)^{\left(\frac{1}{x}\right)}\left(\frac{q_n}{q_a}\right)^{\frac{1}{x}}}{\left(\frac{q_a}{k_d}\right)} = \left(\frac{q_n}{k_d}\right)^{\frac{1}{x}}$$

$$= \left(\frac{1.33}{0.32}\right)^{\frac{1}{0.42}}$$

$$= 29.72 \text{ lb/in}^2 \ (205.1 \text{ kPa})$$

- Therefore, using equation 7–41, the allowable variation in pressure head for the subunit, ΔH_s, is:

$$\Delta H_s = 2.50\left(h_a - h_n\right)$$
$$\Delta H_s = 2.50\left(34.16 - 29.72\right)$$
$$= 11.1 \text{ lb/in}^2 \text{ or } 25.69 \text{ ft } (76.6 \text{ kPa or } 7.830 \text{ m})$$

(eq. 7–41)

Total system capacity, (Q_s)—Using equation 7–42b with the following input data, we calculate (Q_n);

A = 115.7 acre (46.82 ha)
q_a = 1.41 gal/h (5.337 L/h)
N = 1.0
S_e = 6 ft (1.824 m)
S_l = 24 ft (7.3 m)

$$Q_s = K\frac{A\left(q_a\right)}{N\,S_e S_l}$$
$$= \frac{\left(726 \times 115.7 \times 1.41\right)}{\left(1.0 \times 6 \times 24\right)}$$
$$= 822.5 \text{ gal/min } (3{,}113.2 \text{ L/min})$$

(eq. 7–42b)

Seasonal irrigation efficiency (E_s)—

Using EU = 90%
Obtain TR = 1.00 from table 7–15
LR = 0.0

- 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.
- Because a commercial scheduling service will be employed for this operation and little runoff, leakage, or evaporation is anticipated.

$$TR < 1/(1.0 - LR)$$

- Considering a commercial scheduling service, the seasonal irrigation efficiency (E_s) will be:

$$E_s = EU$$
$$= 95.6\%$$

(eq. 7–18)

Gross seasonal volume (V_i)—Using equation 7–17 with the following input data, we calculate (F_{an}).

ET_s = 36.74 in (933.2 mm)
R_e = 3.7 in (93.98 mm)
W_s = 0
E_s = 90%
A = 115.68 a (46.82 ha)
LR = 0.0

- The annual net depth of application $[F_{(an)}]$ is calculated by equation 7–17.

$$F_{(an)} = \left(ET_s - R_e - W_s\right)$$
$$= (36.74 - 3.7)$$
$$= 33 \text{ in } (838.2 \text{ mm})$$

- The gross seasonal volume of irrigation water required (V_i) is calculated by equations 7–20 and 7–21.

$$F_{sg} = \frac{F_{an}}{E_s\left(1 - LR_t\right)} \qquad \text{(eq. 7–20)}$$

$$V_i = \frac{F_{sg}(A)}{K(1-LR)\frac{E_s}{100}} \qquad \text{(eq. 7–21)}$$

$$V_i = \frac{F_{an}(A)}{12\left(1.0 - LR_t\right)\left(\frac{E_s}{100}\right)}$$
$$= \frac{\left(33 \times 115.7\right)}{\left[12\left(1.0 - 0\right)\left(\frac{90}{100}\right)\right]}$$
$$= 353.5 \text{ acre-ft } (43.6 \text{ ha-m})$$

Seasonal operating time (O_t)—The gross seasonal operating time of irrigation is calculated by equation 7–43 using the following input data:

V_i = 353.5 acre-ft (43.6 ha-m)
Q_s = 822.5 gal/min (3,113.2 L/min)

$$O_t = K\left(\frac{V_i}{Q_s}\right)$$
$$= 5{,}430\left(\frac{353.5}{822.5}\right) \qquad \text{(eq. 7–43)}$$
$$= 2{,}334 \text{ h}$$

(2) 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)—Using the following input data and equations 7–63, 7–51b, and 7–52 to determine the manifold spacing.

Plant spacing in the row: Sp = 24 ft (7.3 m)

Spacing between emitters along the lateral: Se = 6 ft (1.824 m)

Average of design emitter discharge rate: qa = 1.41 gal/h (5.337 L/h)

Inside diameter of drip line: ID = 0.58 in (14.7 mm), from manufacture

Use the Keller Head-loss equation.

Emitter-connection loss equivalent length: fe = 0.4 ft (0.122 m); from figure 7–84

Reduction coefficient to compensate for the discharge along the pipe: F = 0.36, from table 7–24

Allowable subunit pressure head variation that will give an EU reasonably close to the desired design value: ΔHs = 25.69 ft (7.81 m)

- Inspection of the orchard layout shows that three manifolds, each serving rows of 54 trees, would be the fewest to meet the criteria, for example, two manifolds for the west 80 acres (32.38 ha) and one manifold for the east 40 acres (16.19 ha).
- The difference in pressure head (Δh) for the level laterals serving 27 trees on either side of each manifold can be calculated as follows:

$$l = 27 \times S_p = 27 \times 24 = 648 \text{ ft } (197 \text{ m})$$

and

$$q_L = \frac{1}{S_e} \times \frac{q_a}{60} = \frac{n_e q_a}{60} \qquad \text{(eq. 7–63)}$$

$$q_l = \frac{648}{6} \times \frac{1.41}{60}$$
$$= 2.54 \text{ gal/min } (9.613 \text{ L/min})$$

Taking into account the added roughness from the emitter connections to the laterals,

$$L' = L\frac{(S_e + f_e)}{S_e} \qquad \text{(eq. 7–51)}$$

$$L' = 648\left[\frac{(6.0 + 0.4)}{6.0}\right]$$
$$= 691.2 \text{ ft } (210.7 \text{ m})$$

Therefore, using equation (7–52),

$$\Delta h = h_f = F L' K \frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.36 \times 691.2 \times 0.00133 \times \frac{(2.54)^{1.75}}{(0.584)^{4.75}}$$
$$= 22.48 \text{ ft } (6.85 \text{ m}) \qquad \text{(eq. 7–52)}$$

- This Δh is considerably greater than 0.5 ΔH_s and would leave too little margin for differences in pressure head in the manifold.

  The lateral length that would produce h = 0.5ΔH_s = 12.84 feet (3.9 m) can be found directly by using the 22.48-foot (6.85 m) head loss computed for the 648-foot (197 m) long lateral and equation 7–66b.

$$L_b \cong L_a\left[\frac{(h_f)_b}{(h_f)_a}\right]^k \qquad \text{(eq. 7–66b)}$$

where:
$(h_f)_b$ = 0.5 x Δh or .5 × 25.69 ft
$(h_f)_a$ = 22.48 calculated from eq.7–52, ft
La = the first selected length, 648 ft

$$L = 648\left(\frac{12.84}{22.48}\right)0.36$$

L = 530 ft (162 m), about 22 trees

This would give a manifold spacing of

$$S_m = 2 \times 22 \times 24$$
$$= 1{,}056 \text{ ft } (322 \text{ m})$$

Thus, the west 80 acres (32.38 ha) of the field could be supplied by three manifolds, but the east half would need two manifolds of different sizes. This is not very convenient.

- Construction will be simplified and management improved by selecting six equally spaced manifolds so that

$$S_m = 27 \times 24$$
$$= 648 \text{ ft } (197 \text{ m})$$

- Where 27 (17+10) is the number of trees on each lateral. Thus, L will be 324 feet (98.5 m), and the new head difference along each pair of laterals can be estimated by again using the 22.48-foot (6.85 m) head loss computed for a 648-foot (197 m)-long lateral in equation 7–66a.

$$(h_f)_b = (h_f)_a \left(\frac{L_b}{L_a}\right)^K$$

$$h_f \cong (22.48)_a \left(\frac{324}{648}\right)^{2.75}$$
$$= 3.34 \text{ ft } (1.01 \text{ m})$$

Determination of manifold position and Δh—If the field was level, the manifolds would be placed every 648 feet with laterals on both sides of 324 feet. But, because of the field slope, the manifold should be shifted to equalize the pressure of the uphill and downhill sides of the manifold. First, start by calculating the friction losses as if the paired lateral were one long lateral of 648 feet. The friction would be the same as the initials selection.

h_f = 22.48 ft (6.85 m)
L = 648
L′ = 691 ft (1.97 m)
F = 0.36
S = 0.5%

- Next determine ΔE:

- Find the tangent location (Y) by using equation 7–67.

$$Y = \left(F \frac{\Delta E}{h_f}\right)^K$$
$$= \left(0.36 \frac{3.24}{22.48}\right)^{0.57} \qquad \text{(eq. 7–67)}$$
$$= 0.19$$

- The manifold position can now be located by satisfying equation 7–68 or by using table 7–26.

$$\frac{\Delta E}{h_f} - 0.36 \left[\frac{\Delta E}{h_f}\right]^{K1} = (z)^{K2} - (1-z)^{K2} \qquad \text{(eq. 7–68)}$$

Since equation 7–68 is solved by trial and error, use table 7–26 to determine the manifold location.

- To use the table, first determine the value of $\frac{\Delta E}{h_f}$;

$$\frac{3.24}{22.48} = 0.144$$

and then enter the table with the value of 0.14 and read the x/L or z equals 0.58.

- The value of x/L or z equals 0.58 falls between the 15th and 16th trees from the lower end. Thus, the manifold should be located to supply 16 trees along the downslope laterals and 11 trees along the upslope laterals.

- The maximum pressure head variation (Δh) along the pair of laterals can be determined from equation 7–69 by use of the x/L or z value that represents the actual manifold location selected.

$$\Delta h = \Delta E(1-z) + h_f (1-z)^K \qquad \text{(eq. 7–69)}$$

$$\Delta h = 3.24(0.42) + 22.48(0.42)^{2.75}$$
$$= 3.4 \text{ ft } (1.04 \text{ m}) \qquad \text{(eq. 7–69a)}$$

- To check for the possibility that the maximum Δh may occur at the closed end of the downslope lateral, determine Δh_c using equation 7–70.

$$\Delta E = S \times L/100 = 3.24$$

$$\Delta h_c = \Delta E(Y) - h_f(Y)$$
$$= 3.24(0.19) - 22.48(.19)^{2.75}$$
$$= 0.4 \text{ ft } (0.122 \text{ m})$$

(eq. 7–70)

- Next determine:

  Lateral inlet pressure head (h_l)
  h_a = 78.81 ft (23.958 m)
  h_{fp} = 22.48 ft (6.85 m)
  z = x/L = 0.58
  ΔE = 3.24 ft (0.985 m)

  For pairs of laterals with a constant diameter, the lateral inlet pressure can be determined by equation 7–64a:

$$h_l = h_a + 0.75 h_{fp}\left[z^K + (1-z)^K\right] - \left(\frac{\Delta E}{2}\right)(2z-1)$$

$$h_l = 78.81 + 0.75(22.48)\left[0.58^{3.75} + (1-0.58)^{3.75}\right] - \left(\frac{3.24}{2}\right)(2(0.58)-1)$$

$$h_l = 78.81 + 2.83 - 0.26$$
$$= 81.3 \text{ ft } (24.780 \text{ m})$$

(3) Manifold design

Selecting pipe size for tapered manifolds involves three criteria.

- a balance between the pipe's initial cost and the pumping cost over the pipe's expected life (described in NEH623.0711(e))
- a balance between friction loss, change in elevation, and allowable variation in pressure
- 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 mainline position—

- For economic reasons and for acceptable ΔH, pairs of manifolds extending in opposite directions from a common mainline connection normally should not exceed a total length of 1,500 feet (457.2 m). Therefore, parallel mainlines are needed.
- Mainlines should be positioned so that starting from a common mainline connection, the minimum pressure in a pair of manifolds is equal (like the manifold position for pairs of laterals as described earlier). Because the ground is level in the direction of the manifolds, the pair of manifolds should be of equal length (fig. 7–101).
- There are access roads in place of the center row of trees in the west 80 acres (32.38 ha) and in the east 40 acres (16.19 ha). Therefore, the length of each manifold is:

$$L_m = 27 \times 24 = 648 \text{ ft } (196.992 \text{ m})$$

*Manifold flow rate (q_m)—*The flow rate for a pair of laterals is q_{lp} equals 2.54 gallons per minute (9.61 L/min).

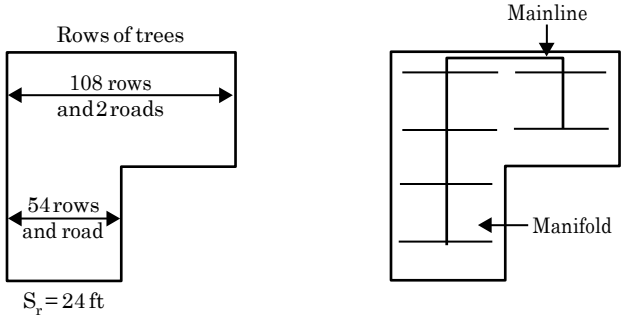
The manifold flow rate is the number of pairs of laterals along each manifold times the flow rate per pair:

$$q_m = 27 \times 2.54$$
$$= 68.58 \text{ gal/min } (259.6 \text{ L/min})$$

*Economic chart method of manifold design—*The economic chart method for designing manifold uses the following input data.

O_t = 2334 h
P_{uc} = \$0.0636/kWh
CRF = 0.205 (20% for 20 yr)
EAE(r) = 1.594 (9% inflation)
E_p = 75%

Figure 7–101 Manifold layout



BHP/Pu = 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 = 68.6 gal/min (259.6 L/min)

q_m = 68.6 gal/min (259.6 L/min)

q_{lp} = 2.54 gal/min (9.61 L/min)

L_m = 648 ft (196.992 m)

ΔH_s = 25.69 ft (7.830 m)

Δh = 3.4 ft (0.790 m)

- 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.

- Compute the cost per water horsepower per season using equation 7–58.

$$C_{whp} = \frac{(O_t)(P_{uc})(EAE_{(r)})}{\left[\left(\frac{BHP}{E_p}\right)\left(\frac{}{P_u}\right)\right]} \qquad \text{(eq. 7–58)}$$

$$C_{whp} = \frac{(2{,}334)(0.0636)(1.594)}{(1.2)\left(\frac{75}{100}\right)}$$

$$= \$263/\text{whp/year}$$

- Using equation 7–59, determine the adjustment factor (A_f), then use equation 7–60 to adjust Q_s to Q_s' for entering the proper unit economic pipe size selection chart.

$$A_f = \frac{0.001C_{whp}}{(CRF)(P_c)} \qquad \text{(eq. 7–59)}$$

$$A_f = \frac{(0.001 \times 263)}{(0.205)(1.00)}$$

$$= 1.28$$

and

$$Q_s' = A_f Q_s' \qquad \text{(eq. 7–60)}$$

$$Q_s' = 1.28 \times 68.6$$

$$= 88 \text{ gal/min } (227.1 \text{ L/min})$$

- The maximum pressure in this and most other typical drip systems is less than 100 psi (690 kPa). Thus, PVC pipe with the minimum available (or allowable) pressure rating can be used. Figure 7–92 is the unit economic pipe size selection chart for this set of PVC pipe sizes.

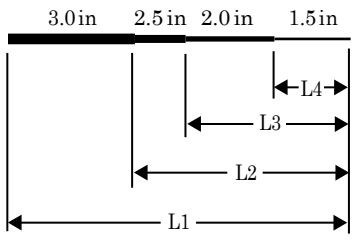
- Enter the vertical axis of figure 7–92 with Q_s' = 88 gallons per minute (227.1 L/min). Record the flow rate (horizontal axis) where the 88 gallons per minute (227.1 L/min) line intersects the upper limit of each pipe size region, which is shown in the table 7–30. The layout of the manifold is shown in figure 7–102.

Table 7–30 Flow rate table

Pipe size, in	Chart flow rate, gal/min	Adjusted flow rate,[1] gal/min	Number of outlets	Multiple outlet factor (table 7–24)
1.50	16	$q_4 = 15.24$	6	0.45
2.00	34	$q_3 = 33.02$	13	0.40
2.50	42.0	$q_2 = 43.2$	17	0.39
3.00	68.6	$q_1 = 68.6$	27	0.38

1 Flow rates adjusted for nearest whole number of lateral connections

Figure 7–102 Manifold detail



- Use equation 7–81 to compute the length of pipe of each size, assuming uniform outlet discharge along the entire length of the manifold.

$$L_d = \left(\frac{q_d - q_{(d-1)}}{q_m}\right) L_m \qquad \text{(eq. 7–81)}$$

where:

L_d = length of pipe with diameter d, ft, (m)
q_d = upper-limit flow rate for the pipe with diameter d, gal/min (L/min)
q_{d-1} = upper-limit flow rate for the pipe with the next smaller diameter, gal/min (L/min)
L_m = length of the manifold used in computing q_m, ft (m)

$$L_{1.50} = \left[\left(\frac{33.02-15.24}{68.6}\right)\right] 648$$
$$= 144\,\text{ft}\,(43.9\,\text{m})$$

$$L_{2.00} = \left[\left(\frac{33.02-15.24}{68.6}\right)\right] 648$$
$$= 168\,\text{ft}\,(51.2\,\text{m})$$

$$L_{2.50} = \left[\left(\frac{43.2-33.02}{68.6}\right)\right] 648$$
$$= 96\,\text{ft}\,(29.3\,\text{m})$$

$$L_{3.00} = 648 - (96+168+144)$$
$$= 240\,\text{ft}\,(76.2\,\text{m})$$

- Using equation 7–72, determine the allowable difference in manifold pressure head.

$$(\Delta H_m)_a = \Delta H_s - \Delta h' \qquad \text{(eq. 7–72)}$$
$$(\Delta H_m)_a = 25.7 - 3.4$$
$$= 22.3\,\text{ft}\,(6.8\,\text{m})$$

Check this against ΔH_m. To do this, first determine the head loss from pipe friction (H_f), and because there is no slope along the manifold, $H_f = \Delta H_m$ equals the friction loss along the manifold, $(h_f)_m$.

H_f is determined as follows.

$$H_f = (h_f)_{3.00} + (h_f)_{2.50} + (h_f)_{2.00} + (h_f)_{1.50}$$

For 3.00-inch ID 3.284-inch (83.3 mm), and

$$(h_f)_{3.00} = (F_1 h_{f1} - F_2 h_{f2})$$
$$= [(0.38\times4.97)-(0.39\times1.39)]$$
$$= 1.34\,\text{ft}\,(0.408\,\text{m})$$

For 2.50-inch ID 2.655 (67.7 mm), and

$$(h_f)_{2.50} = (F_2 h_{f2} - F_3 h_{f3})$$
$$= [(0.39\times3.82)-(0.4\times1.83)]$$
$$= 0.76\,\text{ft}\,(0.231\,\text{m})$$

For 2.00-inch ID 2.193 (55.7 mm), and

$$(h_f)_{2.00} = (F_3 h_{f3} - F_4 h_{f4})$$
$$= [(0.40\times4.53)-(0.45\times1.56)]$$
$$= 1.57\,\text{ft}\,(0.48\,\text{m})$$

For 1.50-inch ID 1.754, (44.55 mm), and

$$(h_f)_{1.50} = (F_4 h_{f4})$$
$$= [(0.45\times1.56)]$$
$$= 1.70\,\text{ft}\,(0.21\,\text{m})$$

The field is level so $H_f = \Delta H_m$, and

$$\Delta H_m = (h_{f3})_{3.00} + (h_{f3})_{2.50} + (h_{f3})_{2.00} + (h_{f3})_{1.50}$$
$$= 1.34+0.76+1.57+0.70$$
$$= 4.38\,\text{ft}\,(1.35\,\text{m})$$

This value is less than $(\Delta H_m)_a$ = 22.3 feet (6.8 m). Therefore, pipe sizes selected by economic criteria are acceptable.

Manifold inlet pressure (H_m)—Equation 7–75a is used to determine the manifold inlet pressure head.

h_l = 81.3 ft (24.715 m)
ΔH_m = 4.38 ft (2.402 m)
$\Delta H_m'$ = $0.5H_f + 0.5\,\Delta El = (0.5 \times 4.38) + 0 = 2.19$
Note: ($\Delta El = 0$ since the manifold grade is 0)

$$H_m = h_l + \Delta Hm' \qquad \text{(eq. 7–75a)}$$
$$H_m = 81.3 + 2.2$$
$$= 83.5\,\text{ft}\,(25.5\,\text{m})$$

(4) Mainline design

Selecting pipe size for mainlines 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 = 548 gal/min (2074.18 L/min) (2/3 of 822)
A_f = 1.28

- First sketch the mainline layout, indicating lengths of pipe and rates of flow along the various sections of pipe (fig. 7–103).
- The unit economic pipe size selection chart, figure 7–92, is used to select the first set of mainline 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 by using equation 7–60.

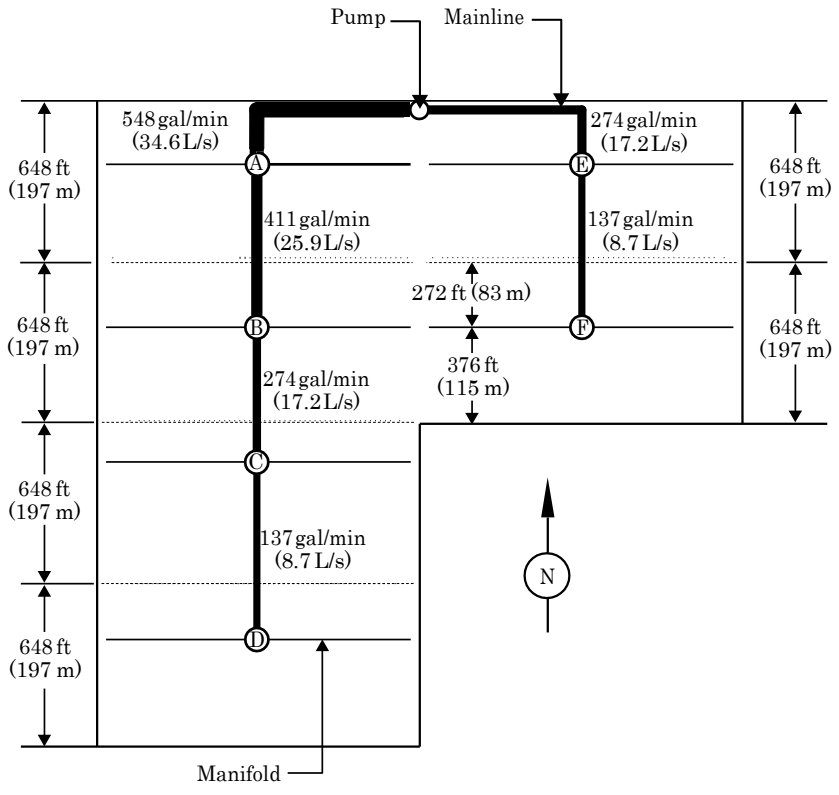
$$Q_s' = A_f Q_s' \qquad (7\text{–}60)$$

$$Q_s' = 1.28 \times 548$$
$$= 701 \text{ gal/min } (44.22 \text{ L/s})$$

- Enter the vertical axis of figure 7–92 with 701 gallons per minute (2,654 L/min), and determine the most economical size of PVC pipe for each flow section. To hold velocities below 5 feet per second (1.52 m/s), stay within the solid boundary lines. After selecting the minimum pipe sizes, determine the friction loss in each section as shown in table 7–31 based on equation 7–52.

$$h_f = F\,L'K\,\frac{Q^{1.83}}{D^{4.83}} \qquad \text{(eq. 7–52c)}$$

Figure 7–103 Orchard layout with final flows and distances



where:
F = 1.0 (table 7–24)

Location of critical manifold inlet—

- 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 7–61.

$$(H_{fe})_m = \sum_{1}^{m} h_f \Delta El \qquad \text{(eq. 7–61)}$$

- The $(H_{fe})_m$ values in table 7–31 show that the critical manifold inlet is at point E, and the pump must supply $(H_{fe})_m$ 3.33 feet (1.14 m) to overcome pipe friction and elevation along the mainlines. The manifolds require the same inlet pressure head if the required H_m is 83.5 feet (25.45 m) and is supplied at point E. All other requirements for manifold inlet pressure head will be more than satisfied.

- 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 should be checked to determine if pipe sizes can be trimmed so that the corresponding manifold inlet points also require $(H_{fe})_m$ is 3.33 feet (1.14 m). This is a small value and, most likely, the pipe sizes will need to remain the same to maximize economic benefits.

Table 7–31 Mainline friction loss for surface drip example

Section	Flow, gal/min	Pipe diameter, in	L, ft	h_f, ft
P–A	548	8	900	4.02
A–B	411	6	648	1.71
B–C	274	6	648	3.26
C–D	137	6	648	0.92)
P–E	274	6	900	4.53
E–F	137	6	648	0.92

Section Point	From–to	Inlet ft	+ h_f ft	Point ± ΔEl	=	$(H_{fe})m$ ft
A	P–A	P=0	+4.02	–1.20	=	2.82
B	A–B	2.82	+1.71	–3.24	=	1.29
C	B–C	1.29	+3.26	–3.24	=	1.31
D	C–D	1.631	+0.92	–3.24	=	1.01
E	P–E	P=0	+4.53	–1.20	=	3.33 1/
F	E–F	3.33	+0.92	–3.24	=	1.01

1 Critical

(5) Total dynamic head

The total dynamic head (TDH) required of the pump is the sum of the items listed in table 7–32.

(6) Filter design

The selection of a filtration system, types, and characteristics of filters are addressed in NEH623.0708. The flowchart in figure 7–95 should be helpful in guiding the selection and design of the filtration system. Data in figure 7–97 indicates that the water quality is relatively high in salinity (EC_w = 1.4 dS/m) and because the orchard is located in the Central Valley of California, some alkalinity can be expected. Assuming the water is a mixture of ground water and surface water (as it often occurs in this area from year to year), a variable pH and some physical and organic contaminants can be expected. Based on the headworks design shown in figure 7–19, a sand media filter backed up by a screen filter, a pressure sustaining valve, air vents and vacuum relief, and a chemical means of controlling the pH (6 < pH < 7) would be a satisfactory design to filter the drip irrigation water for this orchard. The filtration unit should be located by the pump (shown in figure 7–99 at the top center of the figure).

Design the filter using a horizontal sand media tank. The water is relatively clean, so select a flux of 25 gallons per minute per square foot (1,018.569 L/m²). Next, determine the type and size of media to use. Since no manufacturer's recommendation was given, the required filter size is based on the emitter diameter:

0.03/10 = 0.003 in or 76 microns

Table 7–32 Total dynamic head

Items		ft
(1) Manifold inlet pressure head	H_m =	83.5
(2) Pressure head to overcome pipe friction and elevation along the mainline	H_f =	3.33
(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		3.04 4/
Main control valves		0.15 4/
Manifold inlet valve and pressure regulator		6.90 4
Lateral risers and hose bibs		2.30 4/
Safety screens at manifold or lateral inlets		2.30 4/
Lateral or header pressure regulators		5/
(6) Friction-loss safety factor at 10 percent		3.53 6/
(7) Additional pressure head to allow for deterioration of emitters		7/
Total		**138.15**

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 (69 kPa).

3/ Injection pump used.

4/ Taken from manufacturer's or standard charts. Care should be used when specifying safety screens at the manifolds or lateral inlets. Current thinking is that they are a huge maintenance item that affects the uniformity of the blocks and may cause more harm the good.

5/ Not used in this system.

6/ Friction-loss safety factor taken as 10% of lateral (3.34 ft (1.01 m)), manifold (4.38 ft (1.34 m)), mainline (4.53 ft (1.38 m)), and filter (23.1 ft (7.022 m)), 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.

From table 7–18, the required mesh size would be a 200 mesh. From table 7–28 select #20 crushed silica for the media type. For backflushing and maintenance purposes, use a minimum of three tanks. Using equation 7–78, rearrange to solve for tank flow.

$$N_t = \frac{Q_s}{t_f} \qquad \text{(eq. 7–78)}$$

$$N_t = \frac{Q_s}{t_f}$$

$$t_f = \frac{Q_s}{N_t}$$

$$= \frac{822.5}{3}$$

$$= 274 \text{ gal/min}$$

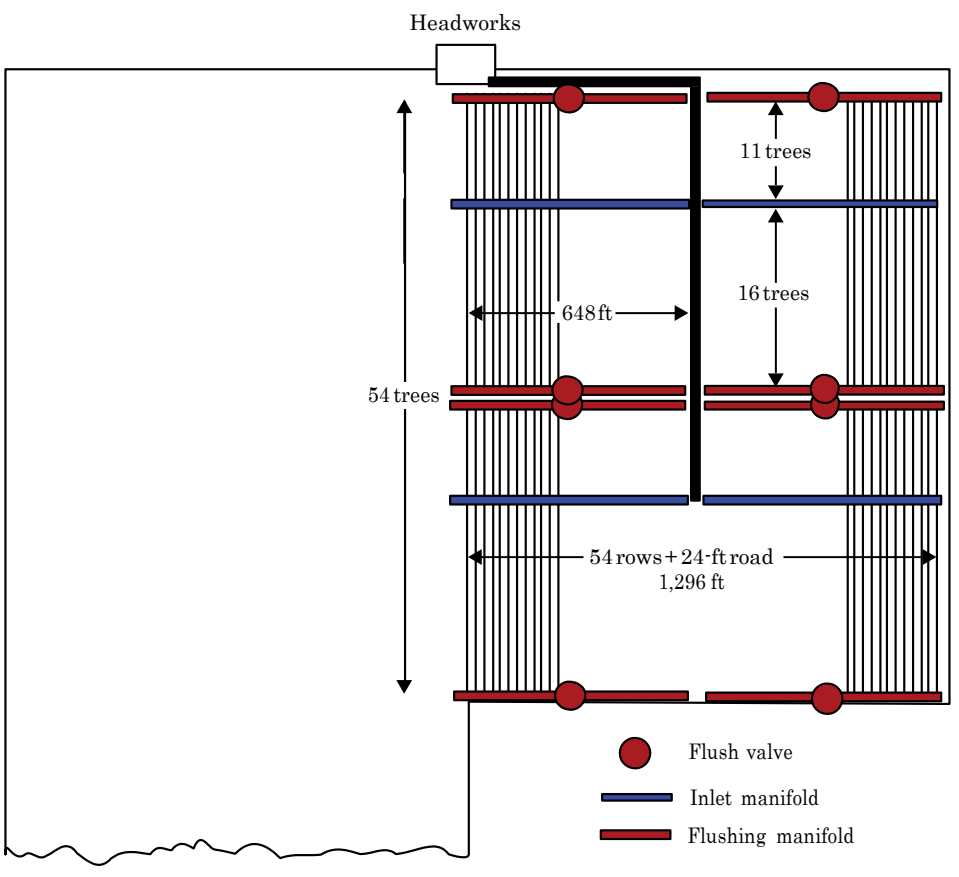
From table 7–27, using 25 gallons per minute flux, select a tank size of 48 inches and from (table 7–29(b)), a backwash flow rate of 60 gallons per minute/tank (227.1 L/min/tank). If a different number of tanks are desired, use the same procedure substituting the desired number of tanks into equation 7–78.

The backwash flow rate is 60 gallons per minute (227.1 L/min), which should be easy to sustain by the pressure sustaining valve, assuming that the pump has adequate pumping capacity. This filtration system has ample capacity to filter unexpected dirty water.

(7) Flushing manifold and minimum flushing velocity

The flushing manifold is level. To keep the pipe size as small as possible, place the valve in the middle and flush from both sides. A flushing manifold (as shown in fig. 7–104) with a cross-sectional area of 25 percent or more of the sum of all the cross-sectional areas of the drip lateral connections is sufficient to maintain a flushing velocity of 1 foot per second (0.304 m/s). The

Figure 7–104 Location of flushing manifolds and flushing valves



flushing manifold diameter can be calculated for the downhill laterals using equation 7–79.

$$D_f = 0.5 D_d \sqrt{N_d}$$
$$= .5 \times 0.58 \sqrt{14}$$
$$= 1.08 \text{ in } (27.4 \text{ mm}) \qquad \text{(eq. 7–79a)}$$

D_f must be rounded up to the next available nominal pipe size, which is 1.5 inches (40 mm).

The same number of laterals are flushed on both the uphill and downhill side of the manifold; therefore, the same pipe can be used for both. For a minimum flushing velocity V_f of 1 foot per second (0.304 m/s), the flushing flow rate from each branch of equal length, Q (gal/min) can be calculated by rearranging equation 7–54.

$$Q_f = \frac{V_f N_d D^2}{0.409}$$
$$= \frac{1 \times 14 \times 0.58^2}{0.409}$$
$$= 11.51 \text{ gal/min } (43.5 \text{ L/min}) \qquad \text{(7–54b)}$$

Each block will have two flushing valves, one for the uphill laterals and one for the downhill laterals. The friction loss for a level-grade flushing manifold can be calculated by equation 7–52. The equivalent length connection loss is 0.4 foot.

$$h_f = F L' K \frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.39 \times 324 \left(\frac{24 + 0.4}{24}\right) 0.00133 \frac{11.51^{1.75}}{1.754^{4.75}}$$
$$= 0.85 \text{ ft. } (0.26 \text{ m})$$

For the complete flush valve, assembly shown in figure 7–96, the flush valve size D_v (mm) can be calculated using equation 7–80. The valve handles flow from both sides, so Q_v is double the manifold flow rate.

$$D_v = K_v \frac{\sqrt{Q_v}}{(P_v)^{0.25}}$$
$$= 0.22 \frac{\sqrt{23.02}}{0.43^{0.25}}$$
$$= 1.3 \text{ in } (33.1 \text{ mm}) \qquad \text{(eq. 7–80)}$$

where:

K_v = 0.22, (35.7) for a branched flush valve and 0.20, (33.4) for the nonbranched flush valve

Q_v = total flow rate through the flush valve at a flushing velocity of 1 ft/s (0.3 m/s) = 23.02 gal/min, (1.74 L/s)

P_v = allowable pressure loss through the flush valve assembly during flushing ($P_v \leq 1$ ft or 3 Kpa)

Choose a 1.0-inch (25.4 mm) flush valve. By substituting 1.0 inch (25.4 mm) for D_v and rearranging equation 7–80, the actual head loss through the flushing valve can be calculated.

$$P_v = \left[k_v \frac{Q_v}{D_v}\right]^4$$
$$= \left[0.22 \frac{\sqrt{23.02}}{1}\right]^4$$
$$= 1.24 \text{ lb/in}^2 \text{ or } 2.86 \text{ ft } (8.5 \text{ kPa or } 0.87 \text{ m})$$

The total pressure need for flushing, P_f is estimated as the sum of the following pressure/head loss components:

Elevation head along flushline = 0 ft (0 m) for zero slope
Flushline friction loss = 1.33 ft (0.41 m)
Flush valve assembly friction loss = 4.06 ft (1.23 m)
Elevation head from flushline to flush valve outlet = 3 feet (0.91 m)

$$P_d = (0.85 + 2.86 + 3)$$
$$= 6.71 \text{ ft or } 2.9 \text{ lb/in}^2 \ (2.04 \text{ m or } 20.0 \text{ kPa})$$

Figure 7–104 shows the location of flushing manifolds and flushing valves for the eastern portion of the field shown in figure 7–99. The same location pattern of flushing manifolds and flushing valves will be repeated in the two western blocks.

(8) System design summary

The final system-design layout is shown in figure 7–99. The design data are presented in figures 7–97 and 7–100. These three figures, along with a brief write-up 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)

$x = 0.42$
$H_m = 83.5\,ft\,(25.45\,m)$
$\Delta H_m = 2.2\,ft\,(0.67\,m)$
$\Delta h = 3.4\,ft\,(1.04\,m)$
$h_a = 78.81\,ft\,(23.96\,m)$
$e' = 4$
$CV = 0.07$

- Compute the ratio of minimum emitter discharge to average emitter discharge in a subunit by equations 7–44 and 7–45.

$$q_n = q_a \left(\frac{h_n}{h_a}\right)^x \qquad \text{(eq. 7–44)}$$

$$h_n = \left(H_m - \Delta H_m - \Delta h\right) \qquad \text{(eq. 7–45)}$$

$$\frac{q_n}{q_a} = \left[\frac{(83.5 - 2.2 - 3.4)}{78.8}\right]^{0.42} = 0.99$$

- Assuming all the manifolds to be adjusted to the same inlet pressures, final or actual expected system EU will be given by equation 7–40a.

$$EU = 100\left(1.0 - 1.27\frac{CV}{\sqrt{e'}}\right)\frac{q_n}{q_a}$$

$$= 100\left(1.0 - 1.27\frac{0.07}{\sqrt{4}}\right)0.99$$

$$= 94.6\% \qquad \text{(eq. 7–40a)}$$

Net application rate (I_n)

$S_p = 24\,ft\,(7.296\,m)$
$S_r = 24\,ft\,(7.296\,m)$
$e = 4$
$q_a = 1.41\,gal/h\,(5.337\,L/h)$
$EU = 94.6\%$

The net application rate will be given by equation 7–46:

$$I^n = K\left(\frac{EU}{100}\right)\left(\frac{eq_a}{S_p S_r}\right) \qquad \text{(eq. 7–46)}$$

Maximum net daily application rate (I_{mn})—After a breakdown, the system may be operated 24 hours per day to make up for lost irrigation time. The maximum net daily application rate is:

$$I_{mn} = 0.018 \times 24$$
$$= .36\,in/d\ (9.1\,mm/d)$$

All the design calculations can be performed using Microsoft® Excel®, as will be demonstrated for subsequent irrigation designs.

(b) Subsurface drip irrigation system for deciduous almond orchard

The following SDI system design is for a deciduous almond orchard. Figure 7–105 shows the basic components of a SDI system for a typical field crop system; the vacuum relief valves should be place at the highest points in the hydraulic system. The simplifications of the SDI design of the almond orchard shown in figure 7–99 are outlined in figure 7–106. The simplifications are made possible by the use of pressure compensated emitter (PC) with exponent x=0. The data needed before beginning the design are summarized in the drip irrigation design data sheet.

In addition to illustrating the general process for designing a SDI system, the example emphasizes the following procedures.

Step 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).

Step 2: Determining ΔH_s, the allowable variation in pressure head that will produce the desired uniformity of emission.

Step 3: Positioning the manifolds and designing the laterals for sloping rows (not a problem for slightly slopping ground and when using a PC emitter).

Step 4: Designing the manifold and selecting economical pipe sizes for both manifolds and mainlines.

Step 5: Computing system capacity and total dynamic operating-head requirements.

Step 6: Determining filter design.

Step 7: Determining inlet flow and pressure required to provide adequate flushing velocity.

(1) Design factors

Before designing the hydraulic network, the designer must determine the type of emitter, the emitter flow characteristics and S_e, q_a, h_a, ΔH_s, and hours of operation per season (O_t). The type of emitter used will greatly affect the design and economics. For example, the use of a PC emitter with a zero or near zero exponent (x) will significantly simplify the design and increase application uniformity, but may also increase the cost of the system.

The design is similar in all blocks. The inset shown at the bottom right-hand corner of figure 7–106 describes the tapered line sizes identical for all manifolds. Figure 7–107 shows the emitter/lateral/tree row layout which uses two laterals per tree row, a total of eight emitters per tree, and an hourly application rate of 6.32 gallons per hour per tree (23.9 L/h/tree). Experience has shown that the twin lateral design distributes the water and nutrients evenly on both side of the trees and helps stabilize the tree during wind gusts.

Although, this design did not reduce the number of manifolds and the number of flushing manifolds, it reduced the required operating pressure substantially. By doubling the number of laterals and reducing the emission rate of the emitters from 1.41 to 0.79 gallons per hour (3.79 L/h to 2.99 L/h), the application rate of water may more closely approximate the absorption rate of the soil and be better suited for high-frequency irrigation. This design will also spread the water over a larger soil volume and will help minimize surfacing of water in coarse texture soils.

Figure 7–105 Subsurface drip irrigation schematic showing basic components for a typical field crop (Phene and Phene 1987)

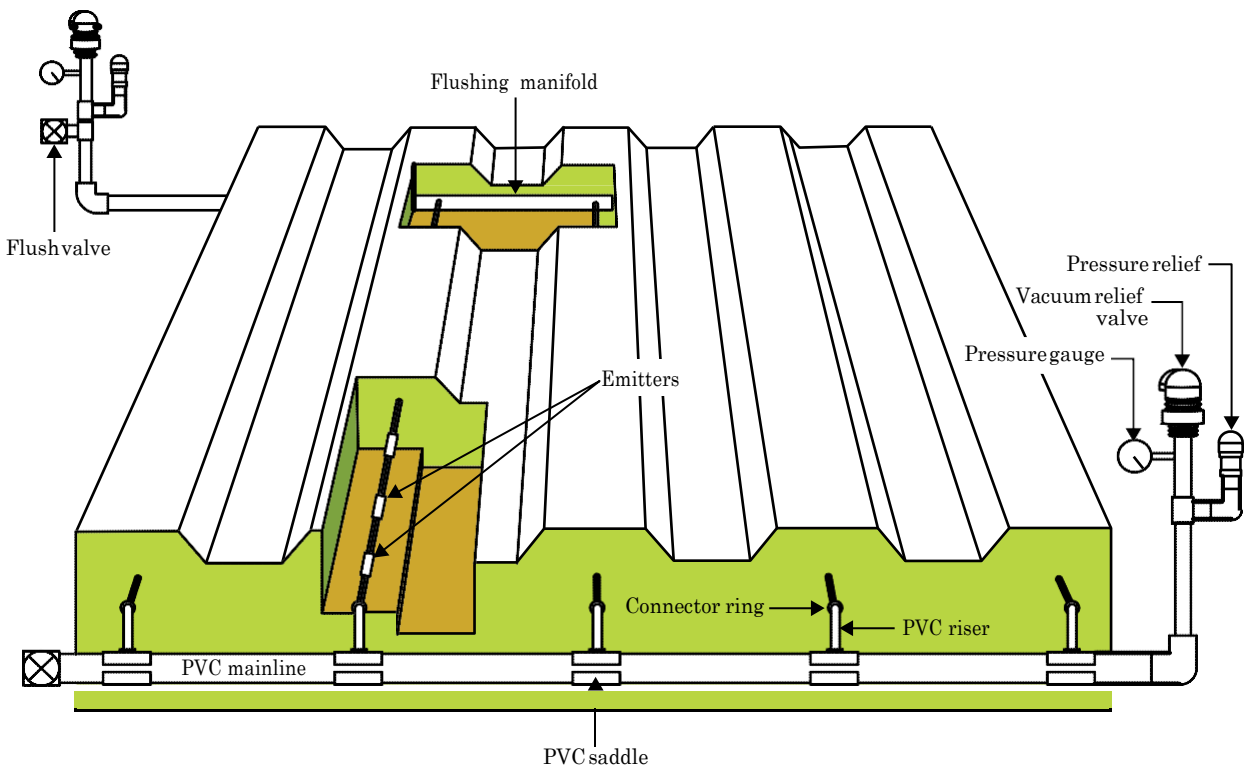
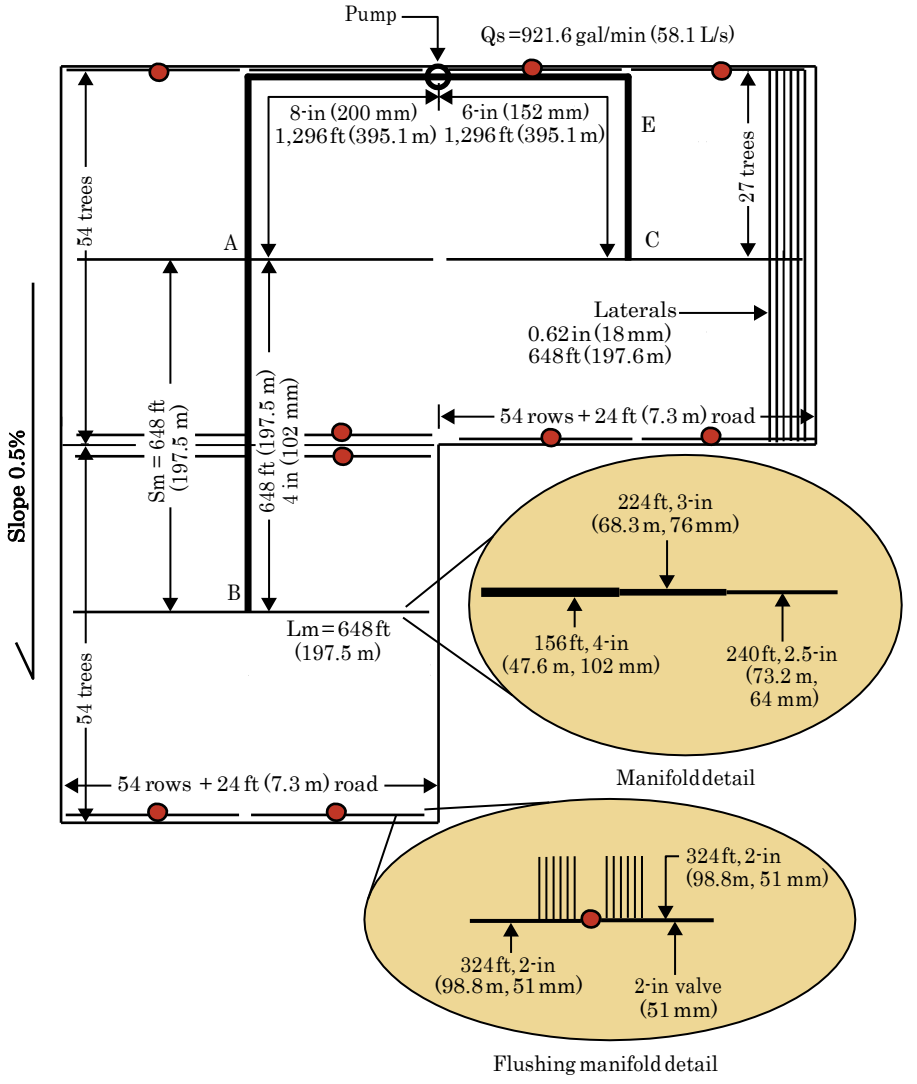


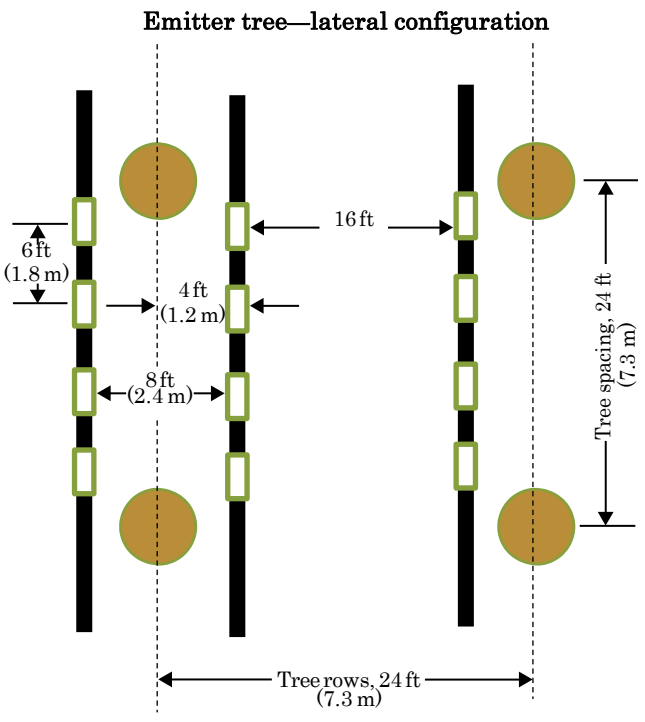
Figure 7–106 Simplified SDI design of almond orchard shown in figure 7–99



Field observations of SDI systems (installed at 1.5 to 2 ft depth (0.456 to 0.608 m)) have shown that the wetted diameter produced by 0.79 gallons per hour (3.0 L/h) emitters is between 5 and 6 feet (1.5 to 1.8 m). For a twin lateral SDI system, a continuous wetted cylinder is not necessary, and the spacing between emitters in the row can exceed 80 percent of the wetted diameter. Therefore, for the 24-foot (7.296 m) tree spacing, a uniform S_e of 6.0 feet (1.824 m) was selected. Table 7–14 can help predict the areas wetted by an emitter; however, field test data and observations at existing systems are preferable.

The emitter/lateral/tree row layout shown in figure 7–107 uses two laterals per tree row, a total of eight emitters per tree, and an hourly application rate of 6.32 gallons per hour per tree (23.9 L/h/tree). The background data on land and water resources and plant and soil and emitter hydraulics are outlined in the MI design factors sheet (fig. 7–108). The initial design data and the final design results are outlined in figure 7–109 and 7–110, respectively. These data sheets serve as a guide and provide a convenient place to record results of the various trial and final computations.

Figure 7–107 The emitter/lateral/tree row layout



Percent area wetted (P_w)—The wetted perimeter is calculated with equation 7–9 where: e = 8; $S_e' = 0.8 \times 6 = 4.8$ feet; $S_w = 4.0$ feet; $S_p = 24$ feet; $S_r = 24$ feet.

$$P_w = \frac{eS_e'(S_e' + S_w)}{2(S_p S_r)} \times 100$$

$$= \frac{8 \times 4.8 \times (4.8 + 4)}{2 \times 24 \times 24} \times 100$$

$$= 29.3\%$$

This is small, but will be used for the design.

Computations for design

- MAD = 30%; AWC = 1.8 in; RZD = 5 feet; F_{mn} from eq 7–11

$$F_{mn} = (MAD)(WHC)(RZD)(P_w)$$

$$= \frac{30}{100} \times 1.8 \times 5 \times \frac{29.3}{100}$$

$$= 0.79 \text{ in}$$

- Average peak daily ET_c, equation 7–12a, from input sheet $Et_c = 0.28$ in/d
- Maximum allowable irrigation interval, I_f

$$I_f = \frac{Fmn}{ET_c}$$

$$= \frac{0.79}{0.28}$$

$$= 2.8$$

- Choose a design irrigation interval of 1 day. $I_{fd} = 1$ day and calculate

$$Fn = 1.0 \times 0.28 = 0.28 \text{ in/d}$$

- Gross application depth, in F_g (eq 7–15a); Tr = 1.0; Trail EU = 90%

Note: when Tr>1/(1–LR) or when LR<0.1, no extra leaching is required. In this case, leaching will be required.

$$F'c = \frac{\text{Salt tolerance of crop } (EC_t)}{\text{Electrical conductive of irrigation water } (ECw)}$$

$$= \frac{1.5}{1.4} = 1.07$$

Figure 7–108 SDI system data for a deciduous almond orchard in the Central Valley of California

I	Project Name—Happy Green Farm—SDI	
II	Land and Water Resources	
	(a) Field no.	#2
	(b) Field area, acre (ha), A	115.68
	(c) Average annual effective rainfall, in (mm), R_e	1.7
	(d) Residual stored soil moisture from off-season precipitation, in (mm), W_s	0
	(e) Water supply, gal/min (L/min)	1,000
	(f) Water storage, acre-ft, (ha-m)	—
	(g) Water quality (dS/m), ECw	1.4
	(h) Water quality classification	Relatively high salinity (fig. 7–15)
III	Soil and crop	
	(a) Soil texture	Silt loam
	(b) Available water-holding capacity, in/ft (mm/m) WHC	1.8
	(c) Soil depth, ft (m)	10
	(d) Soil limitations	None
	(e) Management-allowed deficiency (%) MAD	30
	(f) Crop	Almond
	(g) Tree spacing, ft × ft (m × m) $S_p \times S_r$	24 × 24
	(h) Tree root depth, ft (m) RZD	5
	(i) Average daily peak ET_c rate for the month of greatest overall water use, in/d (mm/d). ET_c	0.28
	(j) Season total crop consumptive-use rate, in (mm), ET_s	36.74
	(k) Crop salinity threshold, EC_t	1.5
IV	Emitter	
	(a) Type	Pressure compensated (PC)
	(b) Outlets per emitter	1
	(c) Range of operating pressure for Constant q, lb/in² (kPa), h	7.0–20.0
	(d) Rated discharge @ h gal/h (L/h), q	0.79 for $7 \le h \le 20$
	(e) Discharge exponent, x	0.0
	(f) Coefficient of variability, CV	0.025
	(g) Discharge coefficient, k_d	0.79
	(h) Connection loss equivalent, ft (m), fe	0.4
	(i) Spacing between emitters along a lateral, ft (m) S_e	6.0
	(j) Emitter line inside diameter, in (mm)	0.62
	(k) Emitter orifice diameter, in (mm)	0.035

Figure 7–109 Trial system design factors for a deciduous almond orchard in the California Central Valley irrigated by a SDI system

Drip system design factors	Symbol	Value
Trial design		
(a) Emission point layout		Twin lateral
(b) Emitter spacing, ft (m)	Se	6
(c) Emission points per plant (4 each lateral)	e	8
(d) Percent area wetted (%)	Pw	29.3
(e) Maximum net depth of application, in (mm)	Fmn	0.79
(f) Ave. peak-of-application daily evapotranspiration rate, in/d (mm/d)	ETc	0.28
(g) Maximum allowable irrigation interval (d)	If	2.8
(h) Design irrigation interval (d)	Ifd	1
(i) Net depth of application, in (mm)	Fn	0.28
(j) Emission uniformity (%)	EU	98.9
(k) Leaching requirement ratio	LR	0.15
(l) Gross water application, in (mm)	Fg	0.33
(m) Gross volume of water required/plant/d, gal/d (L/d)	F(gal/d)	118.4
(n) Time of application, h/d	Ta	19
(o) Water supply (sustainable pumping rate), gal/min (L/min)	WSr	1,000
(p) Inside diameter of drip line, in (mm)	D	0.62

Figure 7–110 Final system design factors for a deciduous almond orchard in the Central Valley of California irrigated by a SDI system

Final design	Symbol	Value
(a) Time of application (h/d)	T_a	19
(b) Design irrigation interval (d)	I_{fd}	1
(c) Gross depth of application at each irrig. in, (mm)	F_g	0.33
(d) Average emitter discharge, gal/h (L/h)	q_a	0.79
(e) Average emitter pressure head, ft (m)	h_a	23.1
(f) Allowable pressure head variation (subunit), ft (m)	ΔH_s	30
(g) Emitter spacing, ft (m)	S_e	6
(h) Percent wetted area (%)	P_w	29.3
(i) Number of stations	N	1
(j) Total system capacity, gal/min (L/min)	Q_s	921.6
(k) Seasonal irrigation efficiency (%)	E_s	98.9
(l) Gross seasonal volume, acre-ft (m^3)	V_i	402
(m) Seasonal operating time (h)	O_t	2,369
(n) Total dynamic head, ft (m)	TDH	101.6
(o) Emission uniformity (%)	EU	98.9
(p) Net application rate, in/h (mm/h)	I_{nR}	0.0174
(q) Maximum net daily application, in (mm)	I_{mn}	0.42
(r) Total filter area perpendicular to flow, ft^2 (m^2)	A_{pf}	36.84
(s) The minimum number of filter tanks, (rounded up to next integer)	N_t	3.00
(t) Minimum backwash flow rate from table 7–29b, gal/min, (L/s)	B_{fM}	72.0
(u) Nominal flushing line diameter, in (mm)	$D_{f(d)}$	2
(v) Flushing Q into each branch of=length, downhill manifold, gal/min (L/min)	$Q_{(d)}$	25.4
(w) Flushing valve diameter for downhill laterals, in (mm)	$D_{v(d)}$	1.5
(x) Required flushing pressure, lb/in^2 (kpa)	P_f	2.19
(y) Lateral spacing, ft (m)	S_l	12.00
(z) Inside diameter of drip line (in, mm)	D	0.62
(aa) Lateral length, ft (m)	L	648
(ab) Manifold length, ft (m)	L_m	648
(ac) Number of blocks	B	6
(ad) Water supply (sustainable pumping rate), gal/min (L/min)	WS_r	1,000.00

Leaching requirement is then calculated from equation 7–23.

$$L_r = \frac{0.1794}{F'c^{3.0417}} = \frac{0.1794}{1.07^{3.0417}} = 0.146$$

Use a LR of 0.15.

$$F_g = \frac{(F_n T_r)}{EU(1-L_r)} \times 100$$

$$= \frac{28 \times 1}{98.9(1-0.15)} \times 100 = 0.33 \text{ in}$$

- Gross volume of water required per plant per day, gal/day, (eq 7–16)

$$F_{(gp/d)} = K \left[\frac{S_p S_r F_g}{I_f} \right]$$

$$= 0.623 \left[\frac{24 \times 24 \times 0.33}{1} \right]$$

$$= 118.4 \text{ gal/d}$$

- Determine time of application T_a, hour per day for each block (eq 7–37) ; $q_a = 0.79$

$$T_a = \frac{F_{(gp/d)}}{eq_a}$$

$$= \frac{118.4}{8 \times 0.79}$$

$$= 18.7 \text{ h} \qquad \text{(eq. 7–37d)}$$

- Use one station 19 hours of operation per day.
- Pressure variation and design EU—because of the pressure compensating qualities of the emitters, the emitter becomes the pressure control and, as long as the minimum operating pressure (plus some factor of safety) is maintained, any pressure variation will not affect the flow rate of the emitter. Therefore, the only thing affecting the emission uniformity is the manufacturer's coefficient of variation (CV). This allows the design to select the actual EU as the design EU.

$$EU = \left(1.0 - \frac{1.27CV}{\sqrt{e}}\right) \times \frac{q_n}{q_a} \times 100$$

Where $\frac{q_n}{q_a}$ for all intents = 1

$$EU = \left(1.0 - \frac{1.27 \times 0.025}{\sqrt{8}}\right) \times 100 = 98.9$$

- The system flow requirement Q_s is determine next using equation 7–42a; N = 1 station; A=115.7 acres, e = 8; q_a = 0.79 gal/h; S_p = 24 feet; S_r = 24 feet.

$$Q_s = K \frac{A\, e\, (q_a)}{N\, S_p S_r}$$

$$= 726 \frac{115.7 \times 8 \times 0.79}{1 \times 24 \times 24}$$

$$= 921.6 \text{ gal/m}$$

- Seasonal irrigation efficiency, Tr =1 from table 7–15. LR =0.15, because Tr< 1/(1–LR) the seasonal efficiency is equal to EU (eq. 7–18).

$$E_s = EU$$

$$= 98.9\%$$

- Gross seasonal volume (7-18c)

$$F_{(an)} = (ET_s - R_e - W_s)$$

$$= 36.74 - 1.7 - 0.0$$

$$= 35.04$$

$$F_{sg} = \frac{F_{an}}{E_s(1-LR_t)} = \frac{35.04}{98.9/100(1-0.15)} = 41.68 \text{ in}$$

$$V_i = \frac{F_{sg}(A)}{K} = \frac{41.7 \times 115.7}{12} = 402 \text{ acre-ft}$$

- Seasonal operating time, O_t, hours from equation 7–43

$$O_t = K\left(\frac{V_i}{Q_s}\right)$$

$$= 5430 \frac{402}{921.6}$$

$$= 2369 \text{ h}$$

(2) Lateral line design and system layout

Because of the pressure compensating qualities of the emitters, the emitter becomes our pressure control, and as long as the minimum operating pressure (plus some factor of safety) is maintained, everything upstream of the emitter (e.g., laterals, manifolds, mainline) can be designed using economic and velocity restrictions. Divide the orchard into three blocks with a length of 1,296 feet, and place the manifold in the middle for ease of operation. The pressure range for the emitter is 7 to 20 psi. To maintain a low pressure but still have some factor of safety, select 10 psi as the minimum design pressure of the lateral. Calculate the elevation change and friction loss for a lateral diameter of 0.62 inch. To determine the required inlet pressure calculation, the friction loss of the lateral the uphill leg will be the most critical.

$$ql = \frac{L\ q_a}{S_e\ 60} = \frac{648\ 0.79}{6\ \ 60} = 1.42 \text{ gal/min} \qquad \text{(eq. 7–52)}$$

$$h_f = F \times L \times K \frac{Q^{1.75}}{D^{4.75}}$$

$$= 0.38 \times 648 \left(\frac{6+0.4}{6}\right) \times 0.00133 \frac{1.42^{1.75}}{0.62^{4.75}}$$

$$= 6.26 \text{ ft} \qquad \text{(eq. 7–52)}$$

Because of the uphill slope, the gain in elevation will add to the friction. The total loss is calculated.

$$\text{Total loss} = h_f + \Delta El$$
$$= 6.26 + .005 \times 648$$
$$= 9.5 \text{ ft}$$

To keep the minimum operating pressure of 10 psi, the minimum lateral inlet pressure would be 14 psi or 32.3 feet.

Manifold sizing and design—Typically, manifolds are tapered and should have no more than four pipe sizes, with the diameter of the smallest 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 velocity method, which limits the pipe velocity to 5 feet per second. Manifolds will be laid across the slope so there is no elevation variation.

- There are 27 rows of trees on either side of a road. Use equation 7–74 to determine manifold length.

$$L_m = \left(n_r - \frac{1}{2}\right) S_r$$
$$= (27 \times .5)24 = 636 \text{ ft}$$

This design ends up with six blocks of 648 by 1,296 feet watered all together as one station.

The manifold flow rate is calculated by taking the number of rows of trees, 27, times the number of laterals per row, times the lateral flow rate. Use the velocity method and allowable pressure variation to size manifold pipe. Results are displayed in table 7–33. Critical point would be from the pump to point B with 3.08 psi or 7.11 feet.

$$q_m = 27 \times 2 \times 2.84$$
$$= 153.4 \text{ gal/min} \qquad \text{(7–72c)}$$

Use a combination of 4-, 3-, and 2.5-inch pipe. This meets the pressure variation and velocity requirements. Friction loss is calculated using equation 7–52. A summary of the losses are:

F	Q (gal/min)	D (in)	L (ft)	V (ft/s)	hf (ft)
0.38	153.4	4	156	3.43	0.9
0.38	116.48	3	224	4.43	2.79
0.38	56.84	2.5	240	3.39	1.92
				Total	5.72

Because the manifold is laid across the slope, the elevation change is zero, and ΔH_m becomes 5.51 plus 0 or 5.51 feet.

Pressure required at the mainline is then determined by equation 7–75a.

$$H_m = h_l + \Delta H_m$$
$$= 32.3 + 5.51$$
$$= 38 \text{ ft}$$

Mainline design—Selecting pipe sizes for the mainlines is based on economic, pressure, and velocity criteria. A detailed example of the use of the economic-chart method of mainline design was presented in the first design example-drip system. This example will use the 5 feet per second velocity criteria.

- Determine flow rate for each section, then size the pipe to obtain a velocity as close to 5 feet per second without going over. Then, obtain the pressure head required to overcome pipe friction and elevation differences. Use the Hazen-Williams equation with a friction factor of C equals 150 for plastic pipe.

Total dynamic head—The TDH required of the pump is the sum of the following pressure head requirements:

Manifold inlet pressure, ft	47.46
Mainline friction	7.11
Suction friction loss and lift	10
Filter-maximum pressure head differential	23.1
Fertilizer injection	—
Flow meter	3.04
Main control valves	0.15
Manifold inlet valve and pressure regulator	6.9
Lateral risers and hose bibs	2.3
Safety screens at manifold or lateral inlets	2.3
Lateral or header pressure regulators	—
Friction-loss safety factor at 10 percent	3.9
Additional pressure head to allow for deterioration of emitters	—
Total dynamic head (TDH)	106.26

Final emission uniformity (EU)—determine using the following:

$H_m = 38$ ft
$\Delta H_m = 5.51$ ft
$\Delta h = 6.26$ ft
$h_a = 23.1$ ft
$x = 0.0$
$CV = 0.025$
$e = 8$

$$\frac{q_n}{q_a} = \left(\frac{H_m - \Delta H_m - \Delta h}{h_a}\right)^x$$
$$= \left(\frac{38 - 5.51 - 6.26}{23.1}\right)^{0.0}$$
$$= 1.0$$
$$EU = 100\left(1 - \frac{1.27}{\sqrt{e}} CV\right)\frac{q_n}{q_a}$$
$$= 100\left(1 - \frac{1.27}{\sqrt{1}} 0.025\right)1.0$$
$$= 98.9\%$$

- Then, find the net application rates.

$(I_n \text{ and } I_{mn}) - S_p = 24$ ft
$Sr = 24$ ft
$e = 8$
$q_a = 0.79$

$$I_n = 1.604\frac{98.9 \times 8 \times 0.79}{100 \times 24 \times 24}$$
$$= 0.0174 \text{ in/h} \qquad \text{(eq. 7–46)}$$

Table 7–33 Mainline pressures for Almond SDI example

Point	Station From	Station To	Pipe diameter (in)	Flow rate (gal/min)	Distance (ft)	ΔEL (±)	Velocity (ft/s)	Friction loss this section (ft)	Required pressure (lb/in²)
P–A	0	1296	7.84	614.4	1296	-3.24	4.08	7.93	2.03
A–B	1296	2592	5.9	307.2	1296	-6.48	3.61	8.90	3.08
P–C	0	1296	5.9	307.2	1296	-3.24	3.61	8.90	2.45

Critical point would be from the pump to point B with 3.08 psi or 7.11 ft

After a system breakdown, each of the two stations can be operated 12 hours per day to give:

$$t_f = \frac{Q_s}{N_t} = \frac{921.6}{3} = 307.2$$

Filter design—Design the filter using a horizontal sand media tank. The water is relatively clean, so select a flux of 25 gallons per minute per square foot (1,018.569 L/m^2). Next, determine the type and size of media to use. Since no manufacturer's recommendation was given, the required filter size is based on the emitter diameter.

$$\frac{0.035}{10} = 0.0035 \text{ in (90 microns)}$$

From table 7–18, the required mesh size would be a 180 mesh. From table 7–28, select number 16 crushed silica for the media type. For backflushing and maintenance purposes, use a minimum of three tanks. Then, using equation 7–78, rearrange to solve for tank flow.

$$N_t = \frac{Q_s}{t_f} \qquad \text{(eq. 7–78)}$$

$$t_f = \frac{Q_s}{N_t} = \frac{921.6}{3} = 307.2 \text{ gal/min/tank}$$

Then, from table 7–27, using 25 gallons per minute flux, select a tank size of 48 inches. Because of the smaller backflush requirements, select a horizontal tank and from table 7–29(b) a backwash flow rate of 72 gallons per minute per tank. If a different number of tanks are desired, use the same procedure substituting the desired number of tanks into equation 7–78.

The backwash flow rate is 72 gallons per minute, which should be easy to sustain by the pressure sustaining valve, assuming that the pump has adequate pumping capacity. This filtration system has a little extra capacity to filter unexpected dirty water.

Flush manifold design—Because of the paired lateral, there will be a flushing manifold on both the uphill and downhill lateral. Since the manifold sizing is based on velocity and not length, the uphill and downhill manifolds will be the duplicates of each other, and only one design is needed. Set flush velocity to 1 foot per second. To reduce pipe size design for a branched manifold, place the valve in the middle and flush from both ends. Select the manifold diameter using equation 7–79. Number of laterals flowing in the manifold, N_d, would equal 648/24, which results in 27. Use lateral diameter D_d equal to 0.62 inches.

$$D_f = 0.5 D_d \sqrt{N_d} = 0.5 \times 0.62 \sqrt{27} = 1.61 \text{ in}$$

Use a nominal flushing line diameter of 2.0 inches.

Flow rate for each branch is determined by rearranging equation 7–54.

$$Q = \frac{V_f N_d D^2}{0.409} = \frac{1 \times 27 \times 0.62^2}{0.409} = 25.4 \text{ gal/min}$$

- Determine the pressure requirement for flushing. First, determine friction loss for a half of the manifold since each half will be the same. Use equation 7–52.

  1.51=324 ft; q=25.4 gal/min; fe=0.4 ft; Se=6 ft; F=0.38; and Di=2.193 in.

$$h_f = F L' K_v \frac{Q^{1.75}}{D^{4.75}} = 0.38 \times 324 \left(\frac{12+0.4}{12}\right) 0.00133 \frac{25.4^{1.75}}{2.193^{4.75}} = 1.2 \text{ in}$$

Next, determine flushing valve size (eq. 7–80) limit pressure loss to 0.5 psi through the valve; q_L=50.8 gallons per minute; and P_v=0.5 psi.

$$D_v = K_v \frac{\sqrt{Q_v}}{(P_v)^{0.25}}$$
$$= 0.22 \frac{\sqrt{23.02}}{0.43^{0.25}}$$
$$= 1.3 \text{ in } (33.1 \text{ mm})$$

Use 2.0-inch valve. The actual pressure loss is calculated rearranging equation 7–80.

$$P_v = \left[K_v \frac{\sqrt{Q}}{D_v} \right]^4$$
$$= \left[0.22 \frac{\sqrt{50.8}}{2.0} \right]^4$$
$$= 0.38 \text{ lb/in}^2 \text{ or } 0.88 \text{ ft}$$

Finally, the flushing riser height above the lateral is 3 feet. The total pressure requirement is the sum of the valve loss, friction loss, and the elevation difference of the riser.

$$P_f = h_f + P_v + \Delta El_r$$
$$= \frac{(1.2 + 0.88 + 3)}{2.31}$$
$$= 2.19 \text{ lb/in}^2$$

(c) Flow-regulated minisprinkler irrigation system for deciduous almond orchard

The following minisprinkler irrigation system design is for the deciduous almond orchard in A. The data needed before beginning the design are summarized in the orchard layout figures (figs. 7–111 and 7–112) and the drip irrigation design data sheet (fig. 7–113).

In addition to illustrating the general process for designing a MI system, the example emphasizes the following procedures:

- selecting the minisprinkler 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)
- determining ΔH_s, the allowable variation in pressure head that will produce the desired uniformity of emission
- positioning the manifolds and designing the laterals for sloping rows (not a problem for slightly slopping ground and when using a flow-regulated minisprinkler system)
- designing the manifold and selecting economical pipe sizes for both manifolds and mainlines
- computing system capacity and total dynamic operating-head requirements
- determining filter design
- determining inlet flow and pressure required to provide adequate flushing velocity

(1) Design factors

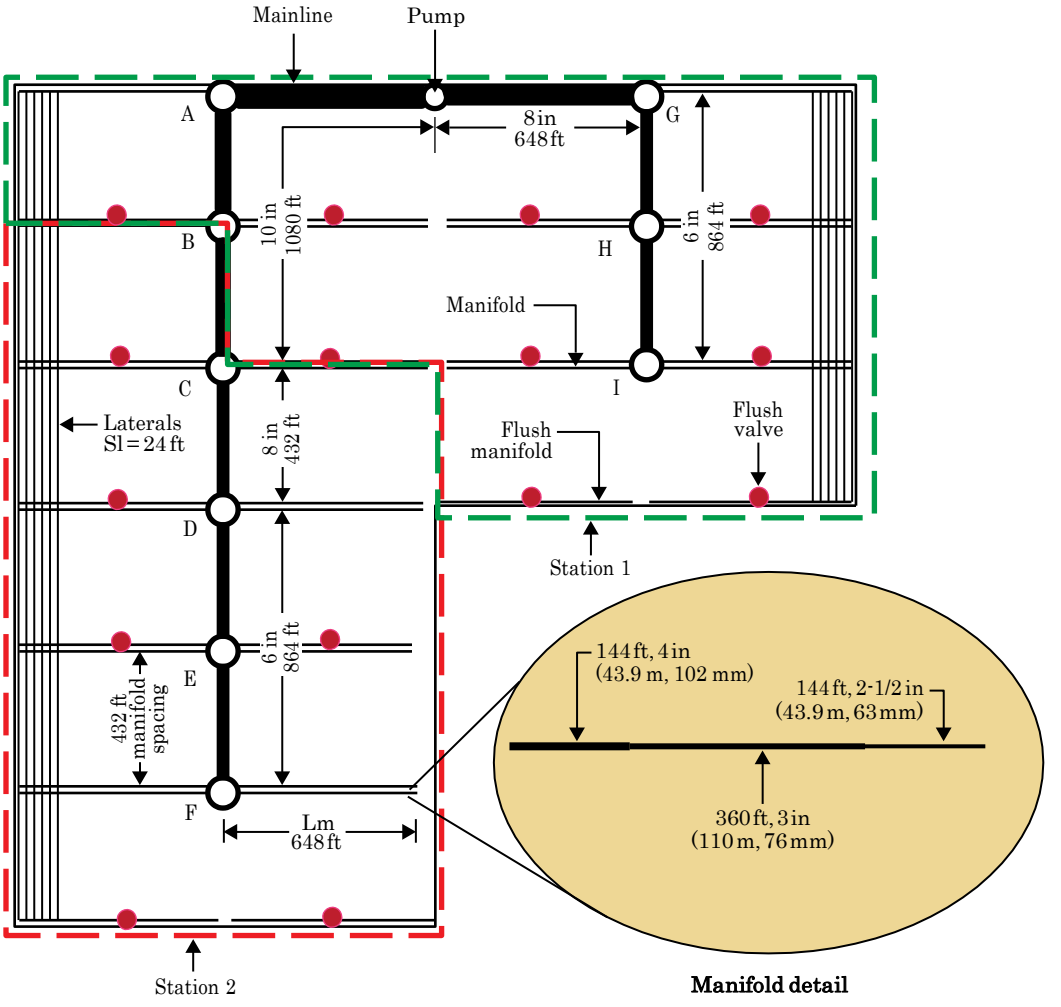
Before designing the hydraulic network, the designer must determine the type of minisprinkler or jet, flow characteristics and spacing (S_e), average minisprinkler discharge rate (q_a), average minisprinkler pressure head (h_a), allowable head variation (ΔH_s), and hours of operation per season (O_t). The type of minisprinkler used will greatly affect the design and economics. For example, the use of a minisprinkler with a zero or near zero exponent (x) will significantly simplify the design and increase application uniformity, but may also increase the cost of the system.

Figure 7–111 shows the simplification of the minisprinkler field design of the almond orchard shown in figure 7–99. The design pattern is identical for all three blocks. The inset shown at the bottom right hand corner shows the manifold design for one lateral per tree row with a total of one minisprinkler per tree.

Field observations of one minisprinkler per tree systems have shown that the wetted diameter produced by 12.4 gallons per hour (46.93 L/h) single minisprinkler per tree at 25 psi (172.4 kPa) pressure is between 16 and 18 feet (4.87 and 5.47 m). Figure 7–112 gives the final sprayer layout, and figures 7–113 through 7–115 give the final design parameters for the project.

Percent area wetted (P_w)—Wetted diameter at 25 psi is 16.4 feet; e equals 1; S'_e for medium texture depth soil equals 3.2; S_p equals 24 feet; and S_r equals 24 feet.

Figure 7–111 Simplified minisprinkler field design for the almond orchard shown in figure 7–99



The surface area wetted by the spray:

$$A_s = \frac{16.4^2\pi}{4} \times \frac{340}{360}$$
$$= 199.5\ ft^2$$

Wetted perimeter (PS):

$$16.4\pi = 51.5\ ft$$

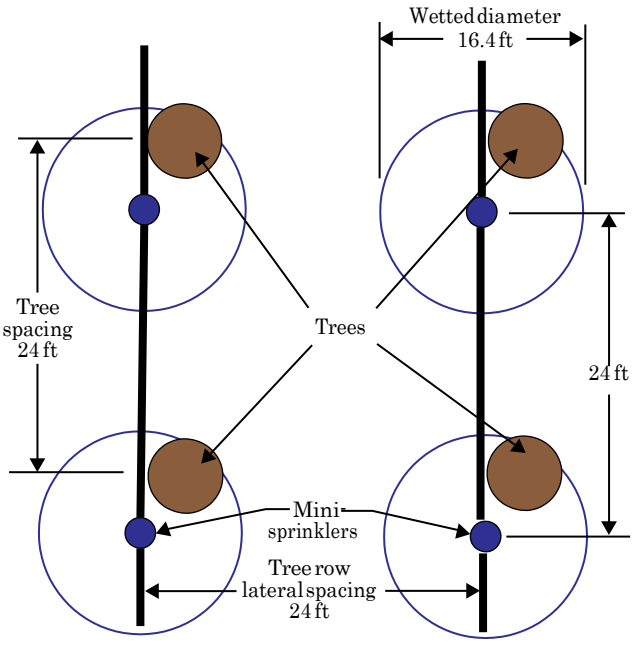
From equation 7–10:

$$P_w = \frac{e\left[A_s + \left(.5S'_e \times PS\right)\right]}{S_p S_r} \times 100$$
$$= \frac{1\left[199.5 + \left(.5 \times 3.2 \times 51.5\right)\right]}{24 \times 24} \times 100$$
$$= 48.9\%$$

This is an acceptable design.

Figure 7–112 The minisprinkler/lateral/tree row-layout

Minisprinkler tree—lateral configuration



Nozzle size, in (mm)	0.039 (0.99)
Discharge rate q_a, gal/h (L/h)	12.4 (46.9)
Wetted diameter, ft (m)	16.4 (5)
Pressure h_a, lb/ft^2 (kPa)	25 (172)
x	0.53
K	2.25

(2) Computations for design

- MAD = 30%; AWC = 1.8 in; RZD = 5 ft; F_{mn} from equation 7–11:

$$F_{mn} = (MAD)(WHC)(RZD)(P_w)$$

$$F_{mn} = (0.30)(1.8)(6.0)(0.3542)$$
$$= 1.15\ in\ (29.1\ mm)$$

- Average peak daily ET_c, equation 7–12a, from input sheet ET_c equals 0.28 inch per day.
- Maximum allowable irrigation interval, I_f

$$I_f = \frac{F_{mn}}{ET_c}$$
$$= \frac{1.32}{0.28}$$
$$= 4.7$$

- Choose a design irrigation interval of 1 day (I_{fd} = 1 day).
- Net depth of application

$$F_n = I_{fd} \times ET_c$$
$$= 1 \times 0.28$$
$$= 0.28\ in$$

- Gross application depth, inch F_g (eq. 7–15a); Tr = 1.0; Trail EU = 90%; LR = 0.0

Note: when Tr>1/(1–LR) or when LR<0.1 no extra leaching is required.

$$F_g = \frac{(F_n T_r)}{EU}$$
$$= \frac{.28 \times 1}{90/100}$$
$$= 0.31\ in$$

- Gross volume of water required per plant per day, gallons per day (eq. 7–16).

$$F_{(gp/d)} = K\left[\frac{S_p S_r F_g}{I_f}\right]$$

CV	0.07
Number emitter/tree	1.0

$$= 0.623 \left[\frac{24 \times 24 \times 0.31}{1} \right]$$

$$= 111.2 \text{ gal/d}$$

Figure 7–113 Minisprinkler system data for a deciduous almond orchard in the Central Valley of California

I Project Name—Happy Green Farm—Minisprinkle Date:_____

II Land and water resources

(a)	Field no.	#3
(b)	Field area, acre (ha), A	115.68
(c)	Average annual effective rainfall, in (mm), R_e	1.7
(d)	Residual stored soil moisture from off-season precipitation, in (mm), W_s	0
(e)	Water supply, gal/min (L/s)	1,000
(f)	Water storage, acre-ft (ha-m)	-----
(g)	Water quality (dS/m) ECw	0.3
(h)	Water quality classification	Excellent (see fig. 7–15)

III Soil and crop

(a)	Soil texture	Silt loam
(b)	Available water-holding capacity, in/ft (mm/m) WHC	1.8
(c)	Soil depth, ft (m)	10
(d)	Soil limitations	None
(e)	Management-allowed deficiency (%), MAD	30
(f)	Crop	Almond
(g)	Tree spacing, ft × ft (m × m). $S_e \times S_r$	24 × 24
(h)	Tree root depth, ft (m), RZD	5
(i)	Average daily peak ET_c rate for the month of greatest overall water use, in/d (mm/d), ET_c	0.28
(j)	Season total crop consumptive-use rate, in (mm), ET_s	36.74
(k)	Leaching requirement (ratio), LR	0

IV Emitter

(a)	Type	Minisprinkler
(b)	Outlets per emitter	1
(c)	Pressure head psi (kPa), h	25
(d)	Rated discharge @ h, gal/h (L/h), q	12.4
(e)	Discharge exponent, x	0.53
(f)	Coefficient of variability, CV	0.07
(g)	Discharge coefficient, k_d	2.25
(h)	Nozzle diameter, in (mm)	0.039
(i)	Wetted circle coverage, °	340
(j)	Wetted diameter, ft (m)	16.4
(k)	Manufacture's screen recommendation	200 mesh
(l)	Spacing between emitters along a lateral, ft (m) S_e	24
(m)	Connection loss equivalent, ft (m), f_e	0.4
(n)	Lateral line inside diameter, in (mm)	1.06

Figure 7–114 Trial system design factors for a deciduous almond orchard in the Central Valley of California irrigated by a minisprinkler system

Minisprinkler system design factors	Symbol	Value
Trial design	**Single lateral**	
(a) Emission point layout		
(b) Emitter spacing, ft (m)	S_e	24
(c) Emission points per plant	e	1
(d) Percent area wetted (%)	Pw	48.9
(e) Maximum net depth of application, in (mm)	F_{mn}	1.32
(f) Average peak-of-application daily evapotranspiration rate, in/d (mm/d)	ET_c	0.28
(g) Maximum allowable irrigation interval (d)	I_f	5
(h) Design irrigation interval (d)	I_{fd}	1
(i) Net depth of application, in (mm)	F_n	0.28
(j) Emission uniformity (%)	EU	90
(k) Leaching requirement ratio	LR	0.0
(l) Gross water application, in (mm)	F_g	0.31
(m) Gross volume of water required/plant/d, gal/d (L/d)	$F_{(gp/d)}$	111.2
(n) Time of application, h/d	T_a	9
(o) Water supply (sustainable pumping rate), gal/min (L/min)	WS_r	1,000
(p) Inside diameter of lateral line, in (mm)	D	1.06

Figure 7–115 Final system design factors for a deciduous almond orchard in the Central Valley of California irrigated by a minisprinkler system

Final Design	Symbol	Value
(a) Time of application (h/d)	T_a	9
(b) Design irrigation interval (d)	Ifd	1.0
(c) Gross depth of application at each irrig. in (mm)	F_g	0.31
(d) Average emitter discharge, gal/h (L/h)	q_a	12.4
(e) Average emitter pressure head, ft (m)	h_a	57.75
(f) Allowable pressure head variation (subunit) ft	ΔH_s	4.04
(g) Emitter spacing, ft (m)	S_e	24.0
(h) Lateral spacing, ft (m)	S_l	24.0
(i) Inside diameter of lateral line in (mm)	D	1.06
(j) Percent wetted area (%)	P_w	48.9
(k) Number of stations	N	2
(l) Total system capacity, gal/min (L/min)	Q_s	904.1
(m) Seasonal irrigation efficiency (%)	E_s	90
(n) Gross seasonal volume, acre-ft (m^3)	V_i	375.4
(o) Seasonal operating time (h)	O_t	2,254
(p) Total dynamic head, ft (m)	TDH	119.34
(q) Emission uniformity (%)	EU	88.7
(r) Net application rate, in/h (mm/h)	I_n	0.031
(s) Maximum net daily application, in (mm)	I_{mn}	0.37
(t) Filter type		Disk
(u) Screen size (mesh)		200
(v) Minimum backwash pressure	B_{fp}	40
(w) Nominal flushing line diameter, in (mm)	D_f	2
(x) Flushing Q into each branch of equal length, gal/min (L/min)	$Q_{(d)}$	38.5
(y) Flushing valve diameter for laterals (rounded up) in (mm)	$D_{v(u)}$	2.50
(z) Pressure requirement needed for flushing, psi, (kpa)	P_f	1.41
(aa) Water supply (sustainable pumping rate), gal/min (L/min)	W_{Sr}	1,000.00

- Determine time of application, T_a, hour per day for each block (eq. 7–37); $q_a = 12.4$

$$T_a = \frac{F_{(gp/d)}}{q_a} = \frac{111.2}{12.4} = 8.97\ h \qquad \text{(eq. 7–37)}$$

- Round up to 9 hours, and use two stations to give 18 hours of operation per day.
- Solve for q_n by rearranging equation 7–14, q_a=12.4 gallons per hour; EU= 90; CV= 0.07; e=1.

$$q_n = \frac{q_a \times EU}{100\left(1.0 - \frac{1.27}{\sqrt{e}}\ CV\right)} = \frac{12.4 \times 90}{100\left(1 - \frac{1.27 \times 0.07}{\sqrt{1}}\right)} = 12.2\ gal/h$$

- Solve for h_n by rearranging equation 7–24.

$$h_n = \left(\frac{q_n}{k}\right)^{\left(\frac{1}{x}\right)} = \left(\frac{12.2}{2.25}\right)^{\left(\frac{1}{.53}\right)} = 24.3\ lb/in^2$$

- Determine the allowable subunit pressure variation ΔH_s psi; h_a equals 25 psi; h_n equals 24.3 psi.

$$\Delta H_S = 2.50(h_a - h_n) = 2.50(25 - 24.3) = 1.75\ lb/in^2\ (4.04\ ft)$$

- The system flow requirement Q_s is determine next using equation 7–42a; N = 2 stations; A=115.7 acres.

$$Q_s = K\frac{A\ e\ (q_a)}{N\ S_p S_r} = 726\frac{115.7 \times 1 \times 12.4}{2 \times 24 \times 24} = 904.1\ gal/min$$

- Seasonal irrigation efficiency, because Tr =1 from table 7–15 and LR =0.0, the seasonal efficiency is equal to EU (eq. 7–18).

$$E_s = EU = 95.6\%$$

- Gross seasonal volume V_i, acre-ft – ET_s=36.74 in; R_e = 1.7 in; W_s =0.0 in; E_s = 90%; A = 115.7 acre.

$$F_{(an)} = (ET_s - R_e - W_s) = 36.74 - 1.7 - .0 = 35.04$$

$$F_{sg} = \frac{F_{an}}{E_s(1 - LR_t)} = \frac{35.04}{90/100(1 - 0.0)} = 38.93\ in$$

$$V_i = \frac{F_{sg}(A)}{K} = \frac{38.93 \times 115.7}{12} = 375.4\ acre\text{-}ft$$

- Seasonal operating time, O_t, hours from equation 7–43.

$$O_t = K\left(\frac{V_i}{Q_s}\right) = 5430\frac{375.4}{904.1} = 2254\ h$$

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—F = 0.38 from table 7–24; f_e = 0.4 ft; S_e = 24 ft; lateral diameter D_i = 1.06 in; q_a = 12.4 gal/h; ΔH_s = 4.04 ft. Select a lateral length of 648 feet; calculate lateral flow rate and friction loss. Try to maintain pressure loss to $0.5\Delta H_s$.

$$ql = \frac{L\ q_a}{S_e\ 60}$$
$$= \frac{648\ 12.4}{24\ \ 60}$$
$$= 5.58 \text{ gal/min}$$

$$h_f = F\ L'K\ \frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.38 \times 648 \left(\frac{24+0.4}{24}\right) 0.00133\ \frac{5.58^{1.75}}{1.06^{4.75}}$$
$$= 5.03 \text{ ft}$$

(eq. 7–52g)

- This is greater than $0.5\Delta H_s$. Calculate new length that will meet loss requirement using equation 7–66b.

$$L_b \cong L_a \left[\frac{(h_f)_b}{(h_f)_a}\right]^k$$
$$= 648 \left[\frac{2.02}{5.03}\right]^{.36}$$
$$= 466 \text{ ft}$$

To simplify construct on the east side, use six manifolds equally spaced at 432 feet; on the west side; use three equally spaced manifolds at 432 feet.

Determine manifold position—Slope = 0.5%

Calculate new lateral flow and friction loss

$$ql = \frac{L\ q_a}{S_e\ 60}$$
$$= \frac{432\ 12.4}{24\ \ 60}$$
$$= 3.72 \text{ gal/min}$$

(eq.7–64)

$$h_f = F\ L'K\ \frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.39 \times 432 \left(\frac{24+0.4}{24}\right) 0.00133\ \frac{3.72^{1.75}}{1.06^{4.75}}$$
$$= 1.72 \text{ ft}$$

$$\Delta E = L \times \frac{\text{slope}}{100}$$
$$= 432 \times 0.005$$
$$= 2.16 \text{ ft}$$

$$\Delta El = -2.16$$

Calculate the tangent location of the friction slope, Y (eq. 7–67).

$$Y = \left(F\ \frac{\Delta E}{h_f}\right)^K$$
$$= \left[0.39\ \frac{2.16}{1.69}\right]^{0.57}$$
$$= 0.67$$

From table 7–26, read the x/l position, z, using ΔE and h_f; enter the table with the following ratio.

$$\frac{\Delta E}{h_f} = 1.27$$

Read z is 0.91. Locate manifold at $0.91 \times 432 =$ 393 ft from bottom end.

$$l_d = 393 \text{ ft}\ l_u = 39 \text{ ft}$$

This would leave only one sprinkler on the uphill side. For easy of construction, move manifold to uphill end of lateral.

The inlet pressure is then determined by equation 7–65c for a single lateral. The lateral friction loss would be h_f=1.72 feet.

$$h_l = h_a + \frac{3h_f}{4} + \frac{\Delta El}{2}$$
$$= 57.75 + \frac{3}{4}(1.72) + \frac{-2.16}{2}$$
$$= 57.96 \text{ ft}$$

The following two pieces of information are also needed to continue with the manifold design Δh and Δh_c.

$$\Delta h = \Delta E - h_f$$
$$= 2.16 - 1.72$$
$$= 0.47$$

$$\Delta h_c = \Delta E(Y) - h_f\,(Y)^{2.75}$$
$$= 2.16(.67) - 1.72(.67)^{2.75}$$
$$= 0.88$$

Typically, manifolds are tapered and should have no more than four pipe sizes, with the diameter of the smallest 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 velocity method, which limits the pipe velocity to 5 feet per second. Manifolds will be laid across the slope so there is no elevation variation.

- There are 27 rows of trees on either side of a road; use equation 7–74 to determine manifold length.

$$L_m = \left(n_r - \frac{1}{2}\right) S_r$$
$$S_r = (27 - .5)24 = 636 \text{ ft} \qquad \text{(eq. 7–74)}$$

This design ends up with 18 blocks of 648 by 432 feet watered in two stations of 9 blocks each.

The allowable pressure variation for the manifold is determined next.

$$\left(\Delta H_m\right)_a = \Delta H_s - \Delta h'$$
$$= 4.04 - 0.82$$
$$= 3.22 \text{ ft} \qquad \text{(eq. 7–72)}$$

where:
$\Delta h'$ = the greater of Δh or Δh_c; in this case Δh is greater

The manifold flow rate is 27 times the lateral flow rate. Use the velocity method and allowable pressure variation to size manifold pipe.

$$q_m = 27 \times 3.72$$
$$= 100.44 \text{ gal/min}$$

Using a multiple outlet factor of 0.38, the total friction loss for the manifold can be calculated as shown.

Q (gal/min)	D (in)	L (ft)	V (ft/s)	hf (ft)
100.44	4.28	144	2.24	0.24
74.4	3.28	360	2.83	1.26
22.32	2.65	144	2.66	0.17
			Total	**1.66**

Because of barb and connection losses, another 0.55 feet are added for local losses. The total now come to 2.36 feet. Calculate $\Delta H_m'$ using equation 7–90.

$$\Delta H_m' = M \times H_f + 0.5\Delta El$$
$$= 0.5 \times 1.66 + 0.5 \times 0$$
$$= 0.83 \text{ ft}$$

Pressure required at the mainline is then determined by (eq. 7–75a).

$$H_m = h_l + \Delta H_m'$$
$$= 57.93 + 0.83$$
$$= 58.76 \text{ ft}$$

Mainline design—Selecting pipe sizes for the mainlines is based on economic, pressure, and velocity criteria. A detailed example of the use of the economic-chart method of mainline design was presented in the first design example. This example will use the 5 feet per second velocity criteria.

- Determine flow rate for each section, then size the pipe to obtain a velocity as close to 5 feet per second without going over. Then obtain the pressure head required to overcome pipe friction and elevation differences. Use the Hazen-Williams equation with a friction factor of C= 150 for plastic pipe. Results are shown in table 7–34.

  Critical point would be from the pump to point H with 2.59 psi or 6.0 feet.

Total dynamic head—The TDH required of the pump is the sum of the following pressure head requirements.

Manifold inlet pressure, ft	58.76
Mainline friction	6
Suction friction loss and lift	10
Filter-maximum pressure head differential	23.1
Fertilizer injection	....
Flow meter	3.04
Main control valves	0.15
Manifold inlet valve and pressure regulator	6.9
Lateral risers and hose bibs	2.3
Safety screens at manifold or lateral inlets	2.3
Lateral or header pressure regulators	....
Friction-loss safety factor at 10 percent	6.6
Additional pressure head to allow for deterioration of emitters TDH	119.13

Determine the final emission uniformity, EU. Where $H_m = 58.76$ ft, $\Delta H_m' = 0.83$ ft, $\Delta h = 0.82$ ft, $h_a = 57.93$ ft, $x = 0.53$, $CV = 0.07$, $e = 1$.

$$\frac{q_n}{q_a} = \left(\frac{H_m - \Delta H_m' - \Delta h}{h_a}\right)^{x}$$

$$= \left(\frac{58.76 - 0.83 - 0.82}{57.93}\right)^{0.53}$$

$$= 0.985$$

$$EU = 100\left(1 - \frac{1.27}{\sqrt{e}} CV\right)\frac{q_n}{q_a}$$

$$= 100\left(1 - \frac{1.27}{\sqrt{1}} 0.07\right)0.9785$$

$$= 89.7\%$$

The net application rates (I_n and I_{mn}) – $S_p = 24$ feet, $S_r = 24$ feet, $e = 1$, $q_a = 12.4$.

$$I_n = 1.604\,\frac{89.7 \times 1 \times 12.4}{100 \times 24 \times 24}$$

$$= 0.031 \text{ in/h}$$

- After a system breakdown, each of the two stations can be operated 12 hours per day to give

$$I_{mn} = 0.031 \times 12$$

$$= 0.37 \text{ in/d}$$

Table 7–34 Mainline friction loss for microspray example

Point	Station From	Station To	Pipe diameter (in)	Flow rate (gal/min)	Distance (ft)	ΔEL (+/–)	Velocity (ft/s)	Friction loss this section (ft)	Required pressure (lb/in²)
P–B	0	1080	10	904.1	1080	–2.16	3.69	4.26	0.91
B–C	1080	1512	10	803.2	432	–2.16	3.28	1.37	0.57
C–D	1512	1944	8	602.4	432	–2.16	3.85	2.38	0.66
D–E	1944	2376	6	401.6	432	–2.16	4.56	4.56	1.70
E–F	2376	2808	6	200.8	432	–2.16	2.28	1.26	1.31

Point	Station From	Station To	Pipe diameter (in)	Flow rate (gal/min)	Distance (ft)	ΔEL (+/–)	Velocity (ft/s)	Friction loss this section (ft)	Required pressure (lb/in²)
P–G	0	648	8	602.4	648		3.85	3.55	1.55
G–H	648	1080	6	401.6	432	–2.16	4.56	4.56	2.59
H–I	1080	1512	6	200.8	432	–2.16	2.28	1.26	2.20

Filter design—Use manufacturer's recommendation of 200-mesh screen; select at least a bank of three that will handle a flow rate of 900 gallons per minute and has auto backflush. Backflush pressure is generally in the range of 40 psi. This should be checked against the TDH requirement to see if the TDH needs to be adjusted higher. In this case, it does not.

Flush manifold design—Set flush velocity to 1 foot per second. To reduce pipe size design for a branched manifold, place the valve in the middle and flush from both ends. Select the manifold diameter using equation 7–79. The number of laterals flowing in the manifold would be 648÷24÷2 = 13.5; use N_d = 14, lateral diameter D_d = 1.06 inches.

$$D_f = 0.5 D_d \sqrt{N_d}$$
$$= 0.5 \times 1.06 \sqrt{14}$$
$$= 1.98 \text{ in}$$

Use a nominal flushing line diameter of 2.0 inches.

- Flow rate for each branch is determined using continuity equation Q = AV and equation 7–54.

$$Q = \frac{V_f N_d D^2}{0.409}$$
$$= \frac{1 \times 14 \times 1.06^2}{0.409}$$
$$= 38.5 \text{ gal/min}$$

- Determine the pressure requirement for flushing. First, determine friction loss for half of the manifold since each half will be the same. Use equation 7–52 where, l = 324 ft, q = 38.5 gal/min, f_e = 0.4 ft, S_l = 24 ft, F = 0.39 (table 7–24) D_i = 2.193 in.

$$h_f = F\ L'K \frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.39 \times 324 \left(\frac{24 + 0.4}{24}\right) 0.00133 \frac{38.5^{1.75}}{2.193^{4.75}}$$
$$= 2.44 \text{ ft}$$

- Next, determine flushing valve size (eq. 7–80) limit pressure loss to 0.5 psi; q = 77 gal/min, P_v = 0.5 psi.

$$D_v = K_v \frac{\sqrt{Q_v}}{(P^y)^{0.25}} = 0.22 \frac{\sqrt{77}}{.5^{.25}} = 2.29 \text{ in}$$

- Use a 2.5 valve. The actual pressure loss is calculated rearranging equation 7–80.

$$P_v = \left[K_v \frac{\sqrt{Q}}{D_v}\right]^4$$
$$= \left[0.22 \frac{\sqrt{77}}{2.5}\right]^4$$
$$= 0.355 \text{ lb/in}^2 \quad (0.82 \text{ ft})$$

- Finally, the flushing riser height is at ground level. The total pressure requirement is the sum of the valve loss, friction loss, and the elevation difference of the riser.

$$P_f = h_f + P_v + \Delta El_r$$
$$= \frac{(2.44 + 0.82 + 0)}{2.31}$$
$$= 1.41 \text{ lb/in}^2$$

(d) Subsurface drip irrigation system for a field crop (cotton)

The following SDI system design is for a cotton crop grown in the San Joaquin Valley of California. The field has similar size, shape, and soil and water characteristics as those of the almond orchard outlined in figure 7–106 and the orchard layout map (figs. 7–110 and 7–99).

Designing a SDI system for a field crop will need to follow similar procedures:

Step 1: Select the emitter or emission point spacing (S_e), lateral spacing (S_l), duration of application (T_a), number of stations (N), and average emitter discharge (q_a) and operating pressure head (h_a).

Step 2: Determine ΔH_s, the allowable variation in pressure head that will produce the desired uniformity of emission.

Step 3: Position the manifolds and design the laterals for sloping rows (not a problem for slightly sloping ground and when using a PC emitter).

Step 4: Design the manifold, and select economical pipe sizes for both manifolds and mainlines.

Step 5: Compute system capacity and total dynamic operating-head requirements.

Step 6: Determine filter design.

Step 7: Determine inlet flow and pressure required to provide adequate flushing velocity.

(1) Design factors

Before designing the hydraulic network, the designer must determine the type of emitter, emitter flow characteristics and spacing (S_e), average emitter discharge (q_a), average emitter pressure head (ha), allowable head variation (ΔH_s), and hours of operation per season (O_t). The type of emitter used will greatly affect the design and economics. This example uses a PC emitter with a zero or near zero exponent (x) and a CV of 0.035. The operating pressure range for the PC emitter is 7 to 25 psi. For field crop applications, more laterals and emitters are needed than for an orchard, so that in this example, the application flow rate will far exceed that used in an orchard, and the 800 gallons per minute (3,028 L/min) capacity is more than tripled.

To meet the sustainable pumping rate of 800 gallons per minute (3,028 L/min), the field is divided into three separate blocks. Each block design is similar, but each block is irrigated separate. The inset shown at the bottom right-hand corner of figure 7–116 describes the field layout for the three identical blocks.

Figure 7–117 shows the emitter/lateral/plant/row layout that uses one lateral per two 30-inch (0.76 m) plant rows, one emitter per 1.75 feet (0.532 m), and an hourly application rate of 0.04 inch per hour (1.0 mm/h).

This design also reduces the number of manifolds from 6 to 3 and the number of flushing manifolds from 12 to 6. By increasing the number of laterals and reducing the emission rate of the emitters from 1.41 gallons per hour to 0.29 gallons per hour (3.785 L/h to 0.984 L/h), the application rate of water may more closely approximate the absorption rate of the soil and is better suited for high-frequency irrigation. This design will also spread the water over a larger soil

Figure 7–116 Design for a field crop SDI system for the field shown in figure 7–99

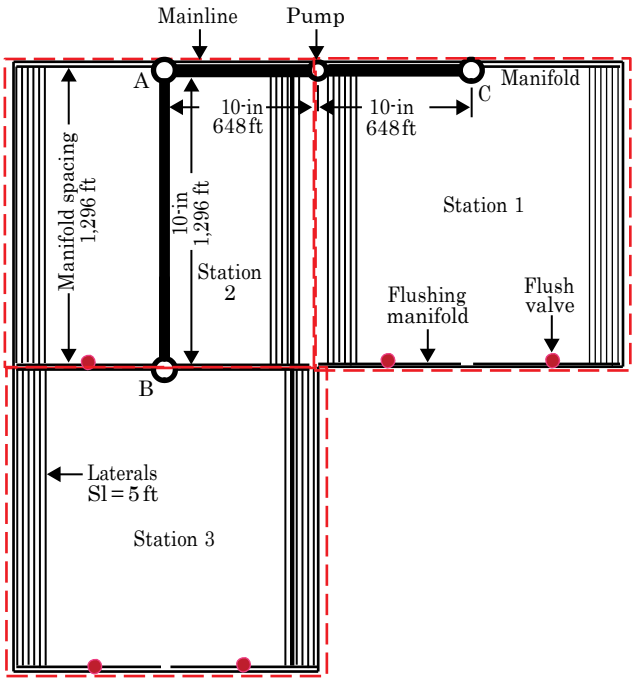
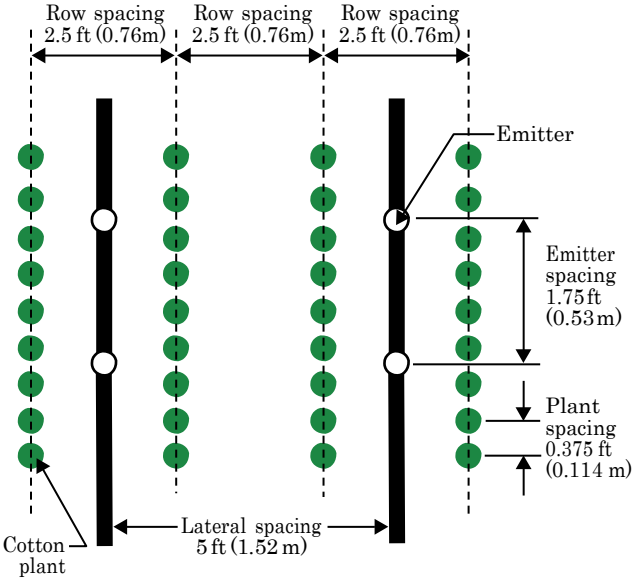


Figure 7–117 Emitter/lateral/plant/row layout



Nonleak, pressure compensated emitter drip hose	
Discharge rate, gal/h (l/h)	0.29 (1.09)
Discharge exponent x	0.0
Pressure range, psi (kPa)	10-60 (69-414)
Wetted strip, ft (m)	2.0 (0.61)
Lateral inside diameter, in (mm)	0.62 (16 mm)

volume and will help minimize surfacing and deep percolation of water in the medium textured soils. Field observations of high-frequency-operated SDI systems (installed at 1.5 to 2 ft (0.456 to 0.608 m) depth) have shown that the wetted diameter produced by 0.29 gallons per hour (0.984 L/h) emitters in a silt loam soil is between 2.0 and 4.0 feet (61 to 1.22 m).

This design is made possible by the use of pressure compensated emitter (PC) with exponent x=0. To stay within the pump capacity, the field is divided into three equal blocks, operated sequentially.

The emitter/lateral/plant/row layout that uses a single, lateral per 5-foot (1.52 m) bed with two rows of cotton, a total of eight plants per emitter with an hourly application rate of 0.04 inch per hour (1.08 mm/h) is shown in figure 7–117.

The background data on land and water resource and plant and soil and emitter hydraulics are outlined in the MI design factors sheet (fig. 7–118). The initial design data and the final design results are outlined in figures 7–118 and 7–119, respectively. These data sheets serve as a guide and provide a convenient place to record results of the various trial and final computations.

Percent area wetted (Pw)—With row crops, the idea is to have a wetted strip along the lateral. The area would be the wetted diameter of the emitter times the length of the lateral. Since the length of the lateral is undetermined, a unit length is used; bed width = 5 feet; wetted diameter or S_w = 2.0 feet.

Figure 7–118 Trial system design factors for a cotton field in the Central Valley of California irrigated by a high-frequency, pressure compensated SDI system

SDI system for field crop (cotton) design factors		Symbol	Value
Trial design			
(a)	Emission point layout		Single lateral
(b)	Emitter spacing, ft (m)	Se	1.75
(c)	Emission points per plant	e	0.107
(d)	Percent area wetted (%)	Pw	40
(e)	Maximum net depth of application, in (mm)	Fmn	1.8
(f)	Ave. peak-of-application daily transpiration. rate, in/d (mm/d)	Td	0.33
(g)	Maximum allowable irrigation interval (d)	If	5.5
(h)	Design irrigation interval (d)	Ifd	1
(i)	Net depth of application, in (mm)	Fn	.33
(j)	Emission uniformity (%)	EU	90
(k)	Leaching requirement ratio	LR	0.0
(l)	Gross water application, in (mm)	Fg	0.37
(m)	Gross volume of water required/plant/day, gal/d (L//d)	F(gp/d)	2
(n)	Time of application, h/d	Ta	7.00
(o)	Water supply (sustainable pumping rate), gal/min (L/s)	WSr	1,000
(p)	Inside diameter of drip line, in (mm)	D	0.875
(q)	Irrigation water quality (dS/m)	EC	1.4
(r)	Plant salt tolerance (dS/m)	EC_t	7.7

From equation 7–8:

$$P_w = \frac{\text{wetted diameter}}{\text{bed width}} \times 100$$

$$= \frac{2}{5} \times 100$$

$$= 40\%$$

This is small, but will be used for the design. In reality, this value should be upwards of 70 percent.

Computations for design

- MAD = 50%; AWC = 1.8 in; RZD = 5 ft; F_{mn} from equation 7–11.

$$F_{mn} = (MAD)(WHC)(RZD)(P_w) \quad \text{(eq. 7–11f)}$$

- Average peak daily ET_c, equation 7–12a, from input sheet Et_c = 0.33 in/d.
- Maximum allowable irrigation interval, I_f

$$I_f = \frac{Fmn}{ET_c} = \frac{1.8}{0.33} = 5.5 \quad \text{(eq. 7–11g)}$$

Figure 7–119 Final system design factors for a cotton field in the Central Valley of California irrigated by a high-frequency, pressure compensated SDI system

Final Design		Symbol	Value
(a)	Time of application, h/d	Ta	7.00
(b)	Design irrigation interval, d	Ifd	1
(c)	Gross depth of application at each irrig., in (mm)	Fg	0.37
(d)	Average emitter discharge, gal/h (L/h)	qa	0.29
(e)	Average emitter pressure head, ft (m)	ha	69.3
(f)	Allowable Pressure Head Variation (subunit)	Hs	115.5
(g)	Emitter spacing, ft (m)	Se	1.75
(h)	Percent wetted area, %	Pw	40
(i)	Number of stations	N	3
(j)	Total system capacity, gal/min (L/min)	Qs	928.2
(k)	Seasonal irrigation efficiency, %	Es	90
(l)	Gross seasonal volume, acre-ft (m^3)	Vi	302.7
(m)	Seasonal operating time, h	Ot	1,771
(n)	Total dynamic head, ft (m)	TDH	168.8
(o)	Emission uniformity, %	EU	96.2
(p)	Net application rate, in/h (mm/h)	In	0.051
(q)	Maximum net daily application rate, in (mm)	Imn	0.41
(r)	Total filter area perpendicular to flow, ft^2 (m^2)	Apf	36.84
(s)	The minimum number of filter tanks (rounded up to next integer)	Nt	3.00
(t)	Minimum backwash flow rate from table 7–29b	BfM	72
(u)	Nominal flushing line diameter for downhill laterals, in (mm)	Df	2.5
(v)	Flushing Q into each branch of length, gal/min (L/min)	Qf	61.2
(w)	Flushing valve diameter, in (mm)	Dv	3
(x)	Pressure requirement for flushing	Pf	2.98
(y)	Lateral spacing, ft (m)	Sl	5.00
(z)	Water supply (sustainable pumping rate), gal/min (L/min)	WSr	1,000
(aa)	Inside diameter of drip line, in (mm)	D	0.62

- Choose a design irrigation interval of 1 day. I_{fd} = 1 d.
- Net depth of application, $F_n = I_{fd} \times ET_c = 1 \times 0.33 = 0.33$ in.
- Gross application depth, inch F_g (eq 7–15a);

  Tr=1.0; Trail EU =90%.

Note: when Tr>1/(1–LR) or when LR<0.1, no extra leaching is required.

$$F'c = \frac{\text{Salt tolerance of crop } (EC_t)}{\text{Electrical conductive of irrigation water (ECw)}} = \frac{7.7}{1.4} = 5.5$$

(eq. 7–22)

Leaching requirement is then calculated from equation 7–23.

$$L_r = \frac{0.1794}{F'c^{3.0417}}$$

No extra water is needed for leaching. Use an LR of 0.0.

The starting EU is our selected design EU, in this case because of the PC emitters; the only variation in flow comes from the manufacturer's variation or CV. Therefore, the design EU can be determined using equation 7–14 with $q_n = q_a$. Where the plant spacing is less than the emitter spacing, the emitter per plant, because one and for all intents and purposes, never becomes less than one.

$$EU = 100\left(1.0 - \frac{1.27CV}{\sqrt{e}}\right)\frac{q_n}{q_a} \times 100$$

The gross application depth now becomes

$$F_g = \frac{F_n}{\frac{EU}{100}} = 0.35 \text{ in/d}$$

With field crops where the crops most times are spaced closer than the emitters, the gross volume of water per plant per day is not relevant, and the emitter spacing can be substituted for the plant spacing.

Equation 7–16 is used to calculate the gallons per day per emitter.

$$F_{(gp/d)} = K\left[\frac{S_p S_r F_g}{I_f}\right] = 0.623\left[\frac{5 \times 1.75 \times 0.37}{1}\right] = 2.0 \text{ gal/d}$$

- Determine time of application, T_a, hours per day for each block (eq. 7–37); with q_a = 0.29.

$$T_a = \frac{F_{(gp/d)}}{eq_a} = \frac{2}{.29} = 6.9 \text{ h}$$

  Use 7 hours. Divide the field into three sets of 7 hours each, which would be a total operating time of 21 hours per day.

- The system flow requirement, Q_s, is determined next using equation 7–42a; N = 3 stations; A=115.7 acres, e = 1, q_a = 0.29 gal/h, S_p = 1.75 ft, S_r = 5 ft.

$$Q_s = K\frac{A\,e\,(q_a)}{N\,S_p S_r} = 726\frac{115.7 \times 1 \times 0.29}{3 \times 1.75 \times 5} = 928 \text{ gal/min}$$

- Then, calculate the seasonal irrigation efficiency, T_r=1 from table 7–15. LR=0.0, because Tr ≤ 1/(1–LR), the seasonal efficiency is equal to EU (eq. 7–18).

$$E_s = EU = 95.6\%$$

- Calculate gross seasonal volume, V_r, acre-ft – ET_s=30 in; R_e = 1.7 in; W_s = 0.0 in; E_s = 95.6%; A =115.7 acres

$$F_{(an)} = (ET_s - R_e - W_s) = 30 - 1.7 - 0.0 = 28.3 \text{ in}$$

$$F_{sg} = \frac{F_{an}}{E_s(1-LR_t)}$$

$$= \frac{28.3}{\frac{95.6}{100}(1-0.0)}$$

$$= 29.6 \text{ in}$$

$$V_i = \frac{F_{sg}(A)}{K}$$

$$= \frac{31.4 \times 115.7}{12}$$

$$= 285.7 \text{ acre-ft}$$

- Seasonal operating time, O_t, hours from equation 7–43.

$$O_t = K\left(\frac{V_i}{Q_s}\right)$$

$$= 5,430\frac{285.7}{928}$$

$$= 1,672 \text{ h}$$

(eq. 7–43e)

Lateral line design and system layout—Because of the pressure compensating qualities of the emitters, the emitter becomes the pressure control, and as long as the minimum operating pressure (plus some factor of safety) is maintained, everything upstream of the emitter (e.g., laterals, manifolds, mainline) can be designed using economic and velocity restrictions. Design the blocks using a single lateral layout (i.e., the manifold is at the head of the lateral), lateral length of 1,296 feet. The pressure range for the emitter is 7 to 25 psi. To maintain a low pressure but still have some factor of safety, select 10 psi as the minimum design pressure of the lateral. Calculate the elevation change and friction loss for the selected lateral diameter.

- L is 1,296 feet; f_e is 0.1 feet per emitter; S_e is 1.75 feet; D_i is 0.875 inches; q_a is 0.26 gallons per hour; F from table 7–24 is 0.38. Use equation 7–63 to calculate lateral flow rate and equation 7–52.

$$ql = \frac{l\ q_a}{S_e\ 60}$$

$$= \frac{1296\ 0.29}{1.75\ 60}$$

$$= 3.57 \text{ gal/min}$$

(eq. 7–63)

$$h_f = F\ L'K\frac{Q^{1.75}}{D^{4.75}}$$

$$= 0.36 \times 1,296\left(\frac{1.75+0.1}{1.75}\right) \times 0.00133\frac{3.57^{1.75}}{0.875^{4.75}}$$

$$= 11.47 \text{ ft}$$

(eq. 7–52)

Because of the downhill slope, the gain in elevation will compensate for some of the friction.

$$\text{Total loss} = h_f - \Delta El$$

$$= 11.47 - .005 \times 1,296$$

$$= 4.98 \text{ ft}$$

$$= 2.15 \text{ psi}$$

To keep the minimum operating pressure of 10 psi, the minimum lateral inlet pressure would 13 psi or 30 feet.

Typically, manifolds are tapered and should have no more than four pipe sizes, with the diameter of the smallest 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 velocity method, which limits the pipe velocity to 5 feet per second. Manifolds will be laid across the slope so there is no elevation variation.

- There are 130 rows of cotton on either side of a road; use equation 7–74a or 7–74b to determine manifold length.

$$L_m = \left(n_r - \frac{1}{2}\right)S_r$$

$$S_r = (27 - .5)24 = 636 \text{ ft}$$

- This design ends up with three blocks of 648 feet by 1,296 feet, each block watered with a set of 7 hours.

The manifold flow rate is 130 times the lateral flow rate. Use the velocity method and allowable pressure variation to size the manifold pipe.

$$q_m = 130 \times 3.57$$

$$= 464.1 \text{ gal/min}$$

Using this flow rate data, the manifold friction losses are calculated.

F	Q (gal/min)	D (in)	L (ft)	V (ft/s)	h_f (ft)
0.36	464.10	7.76	100.	3.15	0.14
0.36	392.70	6.28	300	4.04	1.02
0.36	178.50	4.28	250.	3.91	1.10
				Total	2.12

Add 0.59-foot loss from barb and hose connections; the total manifold losses are 2.71 feet. Calculate $\Delta H_m'$ using equation 7–97.

$$\Delta H_m' = M \times H_f + 0.5\Delta El$$
$$= 0.5 \times 2.71 + 0.5 \times 0$$
$$= 1.35\,\text{ft} \qquad \text{(eq. 7–97)}$$

Pressure required at the mainline is then determined by equation 7–75a.

$$H_m = h_l + \Delta H_m'$$
$$= 30 + 1.35$$
$$= 31.35\,\text{ft} \qquad \text{(eq. 7–75a)}$$

Mainline design—Selecting pipe sizes for the mainlines is based on economic, pressure, and velocity criteria. A detailed example of the use of the economic-chart method of mainline design was presented in the first design example—Drip system. This example will use the 5 feet per second velocity criteria.

- Determine the flow rate for each section. Then, size the pipe to obtain a velocity as close to 5 foot per second without going over. Next, obtain the pressure head required to overcome pipe friction and elevation differences. Use the Hazen-Williams equation with a friction factor of C=150 for plastic pipe. See table 7–35 for summary of mainline friction loss.

  Critical point would be from the pump to point A or C with 1.28 psi or 29.5 feet.

Total dynamic head—The total dynamic head (TDH) required of the pump is the sum of the following pressure head requirements:

Manifold inlet pressure, ft	31.35
Mainline friction, ft	3.0
Suction friction loss and lift, ft	10
Filter-maximum pressure head differential, ft	
Fertilizer injection, ft	....
Flow meter, ft	3.0
Main control valves, ft	0.15
Manifold inlet valve and pressure regulator, ft	
Lateral risers and hose bibs, ft	2.3
Safety screens at manifold or lateral inlets, ft	
Lateral or header pressure regulators	....
Friction-loss safety factor at 10 percent	8.2
Additional pressure head to allow for deterioration of emitters, ft	....
Total Dynamic Head (TDH)	90.4

Table 7–35 Mainline friction loss summary for SDI cotton example

Point P	Station From	To	Pipe diameter (in)	Flow rate (gal/min)	Distance (ft)	Δ EL (+/-)	Velocity (ft/s)	Friction loss this section (ft)	Required pressure (lb/in²)
A	0	648	9.8	928	648		3.95	2.96	1.28
B	648	1,944	9.8	928	1,296	–6.48	3.95	5.92	1.04

Point P	Station From	To	Pipe diameter (in)	Flow rate (gal/min)	Distance (ft)	Δ EL (+/-)	Velocity (ft/s)	Friction loss this section (ft)	Required pressure (lb/in²)
C	0	648	9.8	928	648		3.95	2.96	1.28

- Determine the final emission uniformity, where: H_m is 111.55 ft; ΔH_m is 1.35 ft; Δh is 58.9 ft; h_a is 69.3 ft; x is 0.0; CV is 0.035; and e = 1.

$$\frac{q_n}{q_a} = \left(\frac{H_m - \Delta H_m - \Delta h}{h_a}\right)^x$$
$$= \left(\frac{111.55 - 1.35 - 58.9}{69.3}\right)^{0.0}$$
$$= 1.0$$

$$EU = 100\left(1 - \frac{1.27}{\sqrt{e}} CV\right)\frac{q_n}{q_a}$$
$$= 100\left(1 - \frac{1.27}{\sqrt{1}} 0.035\right)1.0$$
$$= 95.6\%$$

- The net application rates (I_{mn} and I_n) – S_p = 24 ft; S_r = 24 ft; e = 1; and q_a = 12.4.

$$I_n = 1.604\ \frac{96.2 \times 1 \times 0.29}{100 \times 1.75 \times 5}$$
$$= 0.051 \text{ in/h}$$

After a system breakdown, each of the three stations can be operated 8 hours per day to give:

$$I_{mn} = 0.051 \times 8$$
$$= 0.41 \text{ in/d}$$

Design the filter—The water is relatively clean, so select a flux of 25 gallons per minute per square foot (1,018.569 L/m²). Next, determine the type and size of media to use. Since no manufacturer's recommendation was given, the required filter size is based on the emitter diameter:

$$\frac{0.035}{10} = 0.0035 \text{ in (90 microns)}$$

From table 7–18, the required mesh size would be a 180 mesh. Because the laterals are buried, minimize the chances of plugging by using a sand media filter. From table 7–28, select number 16 crushed silica for the media type. For backflushing and maintenance purposes, use a minimum of three tanks. Then, using equation 7–78, rearrange to solve for tank flow.

$$t_f = \frac{Q_s}{N_t}$$
$$= \frac{928.2}{3}$$
$$= 309.4 \text{ gal/min/tank}$$

Then, from table 7–27, using 25 gallons per minute flux, select a tank size of 48 inches. This is on the borderline. Depending on the water source, four tanks may be better to provide a buffer for changes in the water quality. For this design, three 48-inch tanks are used. Because of the smaller backflush requirements, select a horizontal tank and from table 7–29(b), a backwash flow rate of 72 gallons per minute per tank. If a different number of tanks is desired, use the same procedure substituting the desired number of tanks into equation 7–78.

The backwash flow rate is 72 gallons per minute, which should be easy to sustain by the pressure sustaining valve, assuming that the pump has adequate pumping capacity.

Flush manifold design—Set the flush velocity to 1 foot per second. Reduce pipe size design for a branched manifold by placing the valve in the middle, and flush from both ends. Select the manifold diameter using equation 7–79. The number of laterals flowing in the manifold would be N_d = 648/5/2 = 65, lateral diameter D_d = 0.62 inches.

$$D_f = 0.5 D_d \sqrt{N_d}$$
$$= 0.5 \times 0.62 \sqrt{65}$$
$$= 2.49 \text{ in} \qquad \text{(eq. 7–103)}$$

Use a nominal flushing line diameter of 2.5 inches.

Flow rate for each branch is determined using continuity equation Q = AV.

$$Q = \frac{V_f N_d D^2}{0.409}$$
$$= \frac{1 \times 65 \times 0.62^2}{0.409}$$
$$= 61.2 \qquad \text{(eq. 7–104)}$$

- Determine the pressure requirement for flushing. First, determine friction loss for half of the manifold since each half will be the same. Use equation 7–52: 0.5L = 324 ft; q = 25.4 gal/min; f_e = 0.4 ft; Se = 6 ft; F = 0.38 (table 7–24); D_i = 2.655 in.

$$h_f = F\ L'K\frac{Q^{1.75}}{D^{4.75}}$$
$$= 0.36 \times 324\left(\frac{5+0.4}{5}\right)0.00133\frac{61.2^{1.75}}{2.655^{4.75}}$$
$$= 2.17\ \text{ft}$$

Next, determine the flushing valve size (eq. 7–80) limit pressure loss to 0.5 psi, q is 77 gal/min, and P_v is 0.5 psi.

$$D_v = K_v\frac{\sqrt{Q_v}}{(P_v)^{0.25}}$$
$$= 0.22\frac{\sqrt{122.4}}{.5^{.25}}$$
$$= 2.89\ \text{in}$$

Use a 3.0-inch valve. The actual pressure loss is calculated rearranging equation 7–80.

$$P_v = \left[K_v\frac{\sqrt{Q}}{D_v}\right]^4$$
$$= \left[0.22\frac{\sqrt{122.4}}{3.0}\right]^4$$
$$= 0.433\ \text{lb/in}^2\ \ (1\ \text{ft})$$

Finally, the flushing riser height above the lateral is 3 feet. The total pressure requirement is the sum of the valve loss, friction loss, and the elevation difference of the riser.

$$P_f = h_f + P_v + \Delta El_r$$
$$= \frac{(2.17+1.0+3)}{2.31}$$
$$= 2.98\ \text{lb/in}^2$$

623.0713 Field evaluation

Successful MI 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 MI system are:

- duration, frequency, and operation sequence of a normal irrigation cycle
- soil moisture deficit (S_{md}) and management allowed deficit (M_{ad}) in the wetted volume
- rate of discharge at the emission points and pressure near several emitters spaced throughout the system
- changes in rate of discharge from emitters after cleaning or other repair
- percentage of soil volume wetted
- spacing and size of trees or other plants being irrigated
- location of emission points relative to trees, vines, or other plants, and uniformity of emission point spacing
- losses of pressure at the filters
- general topography
- additional data indicated on figure 7–120

(a) Equipment needed

The equipment needed for collecting the necessary field data includes:

- pressure gage (0 to 25 psi range (0 to 34.5 kPa)) with "T" adapters for temporary installation at either end of the lateral hoses
- stopwatch or watch with an easily visible second hand
- graduated cylinder with 250-milliliter capacity
- measuring tape 10 to 20 feet (3.04 to 6.08 m) long

- funnel with 3- to 6-inch (76.2 to 152.4 mm) diameter
- shovel and soil auger or probe
- manufacturer's emitter performance charts showing the relation between discharge and pressure, plus recommended operating pressures and filter requirements
- sheet metal or plastic trough 3 feet (0.912 m) long for measuring the discharge from several outlets in a perforated hose simultaneously or the discharge from a 3-foot (0.912 m) length of porous tubing (a piece of 1 or 2 in (25.4 or 50.8 mm) PVC pipe cut in half lengthwise makes a good trough)
- copies of figure 7–120 for recording data

(b) Field procedure

This 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 7–120 while conducting the field procedure.

Step 1: Fill in parts 1, 2, and 3 concerning the general soil and crop characteristics throughout the field.

Step 2: Determine from the operator the duration and frequency of irrigation and the estimate of the MAD to complete part 4.

Step 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.

Step 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.)

Step 5: Locate four emitter laterals along an operating manifold (fig. 7–86); 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.

Step 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.

Step 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. Collect the flow for a few minutes to obtain a volume between 100 and 250 milliliters 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 8 pressure readings and 32 discharge volumes at 16 plant locations for individual emission points used in wide-spaced crops that have 2 or more points per plant. For perforated hose or porous tubing, use the 3-foot (90.912 m) trough, and collect a discharge reading at each of the 16 locations described. 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. Because the plants are served by only a single emission point, only one reading should be made at each location.

Step 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.

Step 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 inches (0.152

Figure 7–120 Form for evaluation data

1. Location_____, observer_____, date _____
2. Crop: type_____, age_____years, spacing_____ft (m)
root depth_____ft (m) percentage of area covered or shaded_____%
3. Soil: texture_____, available moisture_____in/ft (m/m)
4. Irrig: duration_____h, frequency_____days Mad_____%,_____in (mm)
5. Filter pressure: inlet_____psi (kPa), outlet_____psi, (kPa) loss_____psi (kPa)
6. Emitter: make_____type_____, point spacing_____ft (m)
7. Rated discharge per emission point_____gal/h (L/h),_____at psi (kPa)
Emission points per plant_____, giving_____gal/plant/day (L/plant/d)
8. Hose: diameter_____in (mm), material_____, length_____ft (m), spacing_____ft (m)
9. System layout, general topography, and test locations:

10. System discharge_____gal/min (L/min), no. of manifolds_____and blocks _____
11. Average test manifold emission-point discharges at_____lb/in^2 (kPa)

Manifold = (Sum of all averages, gal/h (L/h))/(Number of averages) = _____gal/h (L/h)

Low 1/4 = (Sum of low 1/4 averages, gal/h (L/h))/(Number of low 1/4 averages) = _____gal/h (L/h)
12. Adjusted average emission-point discharges at_____lb/in^2 (kPa)
System = (DCF[1/]_____) × (manifold average_____gal/h (L/h)) = _____gal/h (L/h)
Low 1/4 = (DCF_____) × (manifold low 1/4_____gal/h (L/h)) = _____gal/h (kPa)
13. Comments:

_____

_____

_____

_____

1/ See item 19.

Figure 7–120 Form for evaluation data—continued

14. Discharge test volume collected in _____ min (1.0 gal/h = 63 ml/min)

Outlet location on lateral	Lateral location on the manifold							
	inlet end		1/3 down		2/3 down		far end	
	ml	gal/h	ml	gal/h	ml	gal/h	ml	gal/h
inlet end	A							
	B							
	Ave.							
1/3 down	A							
	B							
	_____							
	Ave.							
	_____							
2/3 down	A							
	B							
	_____							
	Ave.							
far end	A							
	B							
	_____							
	Ave.							

15. Lateral inlet _____ psi (kPa) _____ psi (kPa) _____ psi (kPa) _____ psi (kPa)
Closed end _____ psi (kPa) _____ psi (kPa) _____ psi (kPa) _____ psi (kPa)

16. Wetted area _____ ft² (m²) _____ ft² (m²) _____ ft² (m²) _____ ft² (m²) _____
per plant _____ % _____ % _____ % _____ %

17. Estimated average SMD in wetted soil volume _____ in (mm)

18. Minimum lateral inlet pressure (MLIP) on all operating manifolds:

Manifold: Test	A	B	C	D	E	F	G	Ave.
Pressure, lb/in² (kPa)	____	____	____	____	____	____	____	____

19. Discharge Correction Factor (DCF) for the system is:

$$DCF = \frac{2.5 \times (\text{average MLIP} _____ \text{psi})}{\text{average MLIP} _____ \text{psi} + 1.5(\text{test MLIP} _____ \text{psi})} = _____$$

Or if the emitter discharge exponent (x) = _____ is known,

$$DCF = \left[\frac{(\text{average MLIP} _____ \text{psi})}{(\text{test MLIP} _____ \text{psi})}\right]^{X} = _____ = _____$$

to 0.304 m) below the surface around each tree. Determine the percent area wetted by dividing the wetted area by the total surface area between four trees.

Step 10: If an interval of several days between irrigations is being used, check the soil moisture deficit (SMD) 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.

Step 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.

Step 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.

Step 13: Determine the average and adjusted average emission-point discharges according to the equations in part 11 and 12.

(c) Using field data

In a MI system, all the 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.

(d) Average depth of application

The average depth applied per irrigation to the wetted area (F_{aw}'), is useful for estimating MAD. It can be computed by equation 7–82.

$$F'_{aw} = \frac{K\left(e \times q'_a \times T_a\right)}{A_w} \qquad \text{(eq. 7–82)}$$

where:

F_{aw}' = average depth applied to the wetted area, in, (mm)

K = 1.604 for English units (1.0 for metric units)

e = Number of emission points per plant

q_a' = Adjusted average emission point discharge of the system, obtained from part 12, figure 7–120, gal/h (L/h)

T_a = application time per irrigation, h

A_W = horizontal area wetted per tree/plant, about 1 ft (0.304 m) below the soil surface, from part 16, fig. 7–20, ft² (m²)

The average depth applied per irrigation to the total cropped area (F_a') can be found by substituting the plant and row spacing ($S_p \times S_r$) for A_W in equation 7–82. Therefore, F_a' can be computed by equation 7–83.

$$F'_a = \frac{K\left(e \times q'_a \times T_a\right)}{\left(S_p \times S_r\right)} \qquad \text{(eq. 7–83)}$$

where:

F'_a = average depth applied per irrigation, in (mm)

(e) Volume per day

The average volume of water applied per day for each tree or plant [$F'_{(gp/d)}$] can be computed by equation 7–84.

$$F'_{(gp/d)} = \frac{K\left(e \times q'_a \times T_a\right)}{I_f} \qquad \text{(eq. 7–84)}$$

where:

e = number of emission points per tree

q_a = adjusted average emission-point discharge of the system, taken from part 12, of figure 7–120, gal/h (L/h)

T_a = application time per irrigation, h

I_f = design irrigation interval, d

(f) 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′ can be computed by equation 7–85.

$$EU'_m = 100\,\frac{q'_n}{q'_a} \qquad \text{(eq. 7–85)}$$

where:

EU' = actual field-emission uniformity, %

q'_n and q'_a = system low-quarter and overall average emitter discharges, taken from NEH623.0712, figure 7–120, gal/h (L/h)

Many drip irrigation systems are fitted with pressure compensating emitters (PC) or have pressure or flow regulation at the inlet to each lateral. However, many 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), psi, throughout the system by equations 7–86 and 7–87.

$$ERF = \frac{\left[\text{average MLIP} + \left(1.5\,\text{minimum MLIP}\right)\right]}{25}\left(\text{average MLIP}\right) \qquad \text{(eq. 7–86)}$$

where:

ERF = efficiency reduction factor, %

Average MLIP = average of the individual MLIP's along each manifold, lb/in^2

Minimum MLIP = lowest lateral inlet pressure in the system, lb/in

The ERF may be estimated more precisely by equation 7–87.

$$ERF = \frac{(\text{minimum MLIP})^x}{\text{average MLIP}} \qquad \text{(eq. 7–112)}$$

In systems where the variations in pressure are small and the emitter discharge exponent (x) is approximately 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:

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 7–36, 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 7–88.

$$EU' = \left(ERF \times EU_m'\right) \qquad \text{(eq. 7–88)}$$

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.

(g) Gross application required

Because drip irrigation wets only a small portion of the soil volume, the SMD must be replaced frequently. It is always difficult to estimate SMD 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, SMD must be estimated from weather data or from information obtained from evaporation devices. Such estimates are subject to error and, because practical ways to check for slight under-irrigation are not widely used, some margin for safety should be allowed. However, the feedback system described in NEH623.0708, figures 7–22 and 7–23 does exactly this by using the feedback from the rate of change of the soil moisture and high-frequency irrigation based on a variable crop coefficient and an automated modified evaporation pan.

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 7–15a or 7–15b. When estimating F_g by equation 7–15a or 7–15b for scheduling irrigations, let EU be the field value (EU′), and estimate the net depth of irrigation to apply (F_n) as:

- Estimate the depth of water that could have been consumed by a full-canopy crop since the previous irrigation (F_n'), inch (mm). This can be estimated by standard techniques based on weather data or pan evaporation data.
- Subtract the depth of effective rainfall since the last irrigation (R_e'), inch.
- Calculate F_n by equation 7–89.

$$F_n = \left(F_n' - R_e'\right) \qquad \text{(eq. 7–89)}$$

Using F_g computed by equation 7–15a or 7–15b, the average daily gross volume of water required per plant per day [$F_{(gp/d)}$] can be computed by equation 7–16.

The average volume of water actually being applied per plant each day [$F_{(gp/d)}'$] is computed by equation 7–84. If [$F_{(gp/d)}$] < [$F_{(gp/d)}'$], the field is being over-irrigated, and if [$F_{(gp/d)}$] > [$F_{(gp/d)}'$], it is underirrigated.

(h) 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), and the uniformity of field emission (EU′). When the unavoidable water losses are greater than the leaching water requirements, $T_r > 1/(1 - LR)$, PE_{lq} can

$$PE_{lq} = \frac{EU'}{T_R\left(1.0 - LR_t\right)} \qquad \text{(eq. 7–90)}$$

and when $T_R < 1/(1.0 - L_R)$, PE_{lq} can be computed by equation 7–91.

$$PE_{lq} = EU' \qquad \text{(eq. 7–91)}$$

where:
PE_{lq} = potential application efficiency of the low quarter, %

The values of T_R appear in conjunction with equation 7–15a and those of L_R with equation 7–24.

A drip 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).

The system PE_{lq} may be low because the manifold inlet pressures are not properly set and ERF (eq. 7–111 and 7–87) 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 over-irrigated, 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 7–92.

$$E_{lq} = 100\,\frac{G}{F2_{(gp/d)}} \qquad \text{(eq. 7–92)}$$

where:
E_{lq} = actual application efficiency, %
G = gross water required per plant during the peak use period, gal/d (L/d)
[$F_{(gp/d)}'$] = average volume of water applied per plant per day, gal/d (L/d)

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_R, or both will not be satisfied. This may cause either excessive buildup of salt along the perimeters of wetted areas or a reduced

be computed by equation 7–90.

l_q volume of wetted soil.

623.0714 Evolving technologies

Low-pressure systems (LPS) are defined similarly as drip irrigation systems except that the water is applied 3 to 4 inches (0.08–0.10 m) below the soil surface through emitters, with discharge rates not exceeding 1.2 gallons per hour (0.76 l/h), like porous tube systems. As mentioned, the interest and uses of DI have increased significantly during the past four decades as understanding of this real time irrigation method increased and plastic materials availability, manufacturing processes, emitter designs, and fertilizers improved. However, the perceived high cost of DI and SDI systems have slowed down the conversion of gravity irrigation to these systems.

The major objective of LPS is to provide a 1- to 2-year life system with advantages of DI and SDI systems, but at a much lower cost. LPS is specifically designed to:

- help growers use existing infrastructures such as leveled fields, water sources, and pumps
- low front-end investment and fast return on investment
- reduce energy cost for pumping and pressurizing
- equipment can be easily moved and reused
- low maintenance and management

Design guidelines, components, and specific installation equipment are being developed and tested. Because of its low-pressure requirement, LPS can operate similarly to gravity irrigation and could potentially replace furrow irrigation. MI performs best when intensive and accurate management of water and nutrients are used. Because of LPS low discharge rate, the use of high-frequency irrigation and rigorous irrigation scheduling necessary for DI and SDI systems is not necessary with LPS.

Figure 7–121 illustrates the downstream end of a large potato field, 800 feet long (250 m) irrigated by a LPS in the Arava Valley, Israel, in 2004. The potato crop is highly uniform across the whole field.

Figure 7–122 illustrates a 300-foot-long (94 m) LPS lateral and the connection to the polynet manifold for a LPS installed at the Maricopa Agricultural Center (University of Arizona) in Arizona, in 2004.

Figure 7–123 illustrates a 300-foot-long (94 m) LPS lateral installed in 2005 on a 60-inch (1.52 m) spacing with two cotton rows per bed at the University of California Shafter Research and Extension Center, Shafter, California.

Figure 7–124 illustrates a 80-inch (2.03 m) bed with two 300-foot-long (94 m) LPS laterals installed in 2005, with two cotton rows per bed at the University of California Shafter Research and Extension Center, Shafter, California.

Data in table 7–31 and figures 7–16, 7–17, and 7–18 support the potential for the application of relatively inexpensive, low-energy drip irrigation technology for irrigating field crops such as potato and cotton. Probably the most important results obtained from this project, conducted in cooperation with the University of California Shafter Research and Extension Center, were the dripperline discharge uniformity measured in August 2005 (table 7–36). These measurements showed very little differences between the 1-year-old systems (first two treatments in table 7–30) and the 2-year-old system (third treatment in table 7–30).

Figure 7–121 The downstream end of a large potato field irrigated using LPS

Figure 7–122 A 300-foot-long (94 m) LPS lateral and the connection to the polynet manifold

Table 7–36 Distribution uniformity of LPS installed in 2004 and 2005 at the University of California, Shafter Research and Extension Center, Shafter, CA

Treatments	Lateral length, ft/acre (m/ha)	Plant Population #/acre (#/ha)	Number of emitter/plant	Manufacturer CV	Distribution uniformity DU	Statistical uniformity U_s
60-in (1.52 m) bed, 1 lateral/bed	8,712 (6,544.3)	44,504 (109,969)	0.1305	0.0257	0.9095	97.43
80-in (2.03 m) bed, 2 laterals/bed	13,068 (9,816.5)	46,602 (115,154)	0.1402	0.0337	0.8857	96.63
40-in (1.01 m) bed, 1 lateral/bed (2nd year)	13,068 (9,816.5)	40,018 (98,885)	0.1633	0.0351	0.8898	96.49

Figure 7–123 A 300-foot-long (94 m) LPS lateral installed in 2005

Figure 7–124 An 80-inch (2.03 m) bed with two 300-foot-long (94 m) LPS laterals installed in 2005 with two cotton rows per bed

623.0715 References

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Appendix A Nomenclature

a	Flow cross section area (in^2)
A	Field area under the system (acres)
A_f	System flow-rate adjustment factor
A_s	Soil surface area directly wetted by the sprayer (ft^2)
A_w	Horizontal are wetted about 1 foot below soil surface (ft^2)
A_{fp}	Total filter area perpendicular to the flow (ft^2)
BHP	Brake horsepower
B_{fm}	Minimum backwash flow rate (gal/min)
c%	Concentration of the desired component in liquid chemical concentrate (%)
c	Number of pipe sizes used in the manifold
C	Desired dosage of chlorine or acid (ppm)
C_f	Friction coefficient for continuous section of pipe
C	Cost of the irrigation system
$C_\$$	Coefficient that depends on the characteristics of the nozzle
c_t	Required tank capacity (gal)
C_{whp}	Annual cost per water horsepower (dollars per water horsepower-season)
CRF	Capital recovery factor
CV	Coefficient of manufacturing variation of the emitter
Df	Flushing line diameter (mm)
d	Flow cross section diameter (in)
D	Inside diameter of pipe (in)
DCF	Discharge correction factor
D_d	Dripper line diameter line (mm)
D_v	Flushing valve diameter (mm)
e	Number of emission points or sprayers per plant
e′	Minimum number of emitter or sprayers from which each plant can obtain water
E	Present annual power cost
E′	Equivalent annual cost of the rising energy cost (9 percent per year)
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)
ΔE	Change in elevation; absolute value always positive
ΔEl	Change in elevation; positive for the laterals running uphill from the inlet and negative for the downhill laterals (ft)
ΔEl	Difference in elevation between the pump and manifold; positive if uphill to manifold and negative if downhill (feet)
ERF	Efficiency reduction factor
Et_c	Crop evapotranspiration rate, in/day, (mm/d)
ET_o	Reference evapotranspiration, short crop (grass), in/d, (mm/d)
ET_s	Seasonal evapotranspiration rate, in/yr
EU	Design emission uniformity (%)
EU′	Uniformity of field emission (%)
EU_m'	Field emission uniformity of the manifold area tested (%)
f	Darcy-Weisbach pipe-friction factor
F	Reduction coefficient to compensate for discharge along the pipe
F_a'	Average depth applied per irrigation to the total cropped area (in)
F_{an}	Annual net depth of application (in)
F'_{aw}	Average depth applied per irrigation to the wetted area (in)
F_c	Concentration of nutrients in liquid fertilizer (lb/gal)
f_e	Emitter connection loss equivalent length (ft)
F_f	Flow capacity per unit area (ft/min)
F_g	Gross depth of application at each irrigation (in)
$F_{(gal/d)}$	Gross volume of water required per day (gal/d)
$F_{(gp/d)}$	Average volume of water applied per plant per day (gal/d)
F_{mn}	Maximum net depth of application (in)
F_n	Net depth of application (in)
F_n'	Depth of water consumed by full canopy crop since previous irrigation (in)

F_r	Rate of fertilizing (lb/acre)
F_s	Manifold pipe-friction adjustment factor
$(F_s)_1$	Friction adjustment for the original manifold
$(F_s)_2$	Friction adjustment factor for the manifold for which $(Hf)^2$ is being estimated
$F_{(sg)}$	Gross seasonal depth of application (in)
g	Acceleration of gravity (32.2 ft/s2)
G	Gross water required per plant during the peak use period (gal/d)
h	Working pressure head of inner main chamber (ft)
h_p	Working pressure head at the emitter (lb/in^2)
H	Time of actual irrigating per irrigation cycle (h)
ΔH	Desired pressure-head increase between two points (ft)
Δh	Difference in pressure head along the laterals
$\Delta h'$	Amount the lateral inlet pressure differs from hectare (ft)
$(100 \times \Delta h/L)'$	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 (ft)
H_a	Average manifold pressure
h_c	Pressure head at the closed end of the lateral (ft)
Δh_c	Difference between the downstream end and minimum pressure heads (ft)
h_e	Friction head loss caused by a specific fitting (ft)
H_f	Pressure-head loss in the manifold from pipe friction (ft)
Hf	Lateral head loss from pipe friction (ft)
${}^{m}\Sigma_i h_f$	Sum of the pipe-friction losses between the pump and manifold inlet at m (ft)
$(h_f)_a$	Original lateral pipe-friction loss (ft)
$(h_f)_b$	New lateral pipe-friction loss (ft)
$h_{(a,b)}$	Difference in head loss between adjacent pipes of different sizes (ft)
$(H_{fe})_m$	Pressure head to overcome pipe friction and elevation along the mainline (ft)
$(h_f)_m$	Friction loss along the manifold (ft)
h_{fp}	Friction loss in a lateral with length (l) (ft)
h_{fx}	Head loss from a point "x"' to the closed end of a multiple-outlet pipeline (ft)
$(H_f)_1$	Pressure-head loss from pipe friction for the manifold (ft)

$(H_f)_2$	Estimated being made of the manifold (ft)
h_l	Lateral inlet pressure head (ft)
H_m	Manifold inlet pressure head (ft)
ΔH_m	Difference in pressure head along the manifold (ft)
$\Delta H_m'$	Amount the manifold inlet pressure differs from h_1 (ft)
$(\Delta H_m)_a$	Allowable manifold pressure variation (ft)
h_n	Pressure head that will give the qn required to satisfy the EU (ft)
H_r	Ratio between fertilizing time and time of actual irrigating per irrigation cycle
ΔH_s	Allowable subunit pressure-head variation that will give an EU reasonably close to the desired value (ft)
h_1	Working pressure of the secondary chamber (ft)
h_1, h_2	Pressure heads corresponding to q_1, q_2, respectively (lb/in^2)
i	Annual interest rate
I_n	Net application rate (in/h)
I_{fmx}	Maximum allowable irrigation interval (d)
I_f	Design interval (d)
k	Conversion constant that is equation specific
K_c	Crop coefficient
k_d	Constant of proportionality (discharge coefficient) that characterizes each emitter
K_f	Friction head-loss for a specific fitting
K_v	35.7 for a branch flush valve and 33.4 for a nonbranched
l	Length of a lateral (ft)
L	Length of a pipeline (ft)
l′	Equivalent length of the lateral with emitter (ft)
l_a	Original lateral pipe length (ft)
l_b	New lateral pipe length (ft)
l_c	Length of the flow path in the emitter (ft)
L_d	Length of pipe with diameter d (ft)
l_m	Length of a single manifold (ft)
L_n	Net leaching requirement for net application (in)
L_N	Annual leaching requirement for net seasonal application (in)

L_p	Length of a pair of manifolds (ft)
L_s	Length of the smaller pipe that will increase the head loss by ΔH (ft)
LR	Leaching requirement ratio
L_1	Length of pipe in the original manifold (ft)
L_2	Length of pipe in the manifold for which (Hf)2 is being estimated (ft)
m	Number of orifices in the secondary chamber per orifice in the main chamber
m′	Number of orifices in series in the emitter
MAD	Management-allowed deficit, which is the desired soil-moisture deficit at the time of irrigation (%)
MLIP	Minimum lateral inlet pressure (lb/in)
Minimum MLIP	Lowest lateral inlet pressure on the system (lb/in^2)
N_d	Number of dripper lines flowing in that branch of the flushing line towards the flush valve
n	Number of emitters in the sample
n_y	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 a manifold
N_r	Reynolds number
$(n_r)_p$	Number of row (or lateral) spacings served from a common inlet point
N_t	Minimum number of filtration tank
O_t	Average pump operating time per season (h)
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 (%)
P_v	Allowable pressure loss through flush valve (kilo Pascal)
P_u	Unit of power
P_{uc}	Unit cost of power (dollars per kilowatt hour)
P_w	Average horizontal area wetted in the crop root zone as a percentage of the total crop area (%)
PE_{lq}	Potential application efficiency of the lower quarter
PS	Perimeter of the area directly wetted by a sprayer (ft)
PW(r)	Present worth factor with energy cost rising at rate, r

q	Emitter discharge rate (gal/h)
$\overline{q}$	Average discharge rate of the emitter samples
Q	Flow rate in the pipe (gal/min)
q_a	Average of design emitter discharge rate (gal/h)
q_a'	Average of all the field-data emitter discharges (gal/h)
q_c	Rate of injection of the chemical into the system (gal/h)
q_d	Upper limit flow rate for the pipe with diameter d (gal/h)
q_{d-1}	Upper limit flow rate for the pipe with the next smaller diameter (gal/min)
q_f	Rate of injection of liquid fertilizer into the system (gal/h)
q_l	Lateral flow rate (gal/min)
$(q_l)_a$	Average lateral (pair) flow rate along the manifold (gal/min)
$(q_l)_c$	Flow rate into the lateral (pair) at the closed end of the manifold (gal/min)
q_{lp}	Flow rate for pair of laterals (gal/min)
q_m	Flow rate in the manifold (gal/min)
q_n	Minimum emission rate computed from the minimum pressure in the system (gal/h)
q_n'	Average discharge of the lowest quarter of the field-data discharge reading (gal/h)
Q_s	Total system capacity or flow rate (gal/min)
Q_s'	Adjusted flow rate for entering the economic design chart (gal/min)
Q_s''	Modified adjusted system flow rate (gal/min)
q_x	Largest flow rate (Q) in the respective table for pipe size in appendix B (gal/min)
q_1	Flow rate in the original manifold (gal/min)
q_s	Flow rate in the manifold for which (gal/min)
q_1, q_s	Discharges (gal/min)
$q_1, q_s \ldots q_n$	Individual emitter discharge rates (gal/h)
Q_v	Total flush rate through the flush valves at 1 ft/s
r	Annual rate of rising energy cost
R_e	Effective rainfall during the growing season (in)
R_e'	Effective rainfall since the last irrigation (in)
RZD	Depth of the soil profile occupied by plant roots (ft)
SD	Unbiased standard deviation of the discharge rates of the sample

S	Average slope of the ground line (%)
S′	Unusable slope component, which is the amount the friction curve needs to be raised (ft)
S_e	Spacing between emitters or emission points along a line (ft)
S_e'	Optimum emitter spacing; drip emitter spacing that provides 80 percent of the wetted diameter estimated from field tests or table 7–2 (ft)
S_f	Shape factor of the subunit
S_t	Lateral spacing (ft)
S_m	Manifold spacing (ft)
SMD	Soil Moisture Deficit; difference between field capacity and the actual soil moisture in the root zone soil at any given time (in)
S_p	Plant spacing in the row (ft)
S_r	Row spacing (ft)
S_w	Width of the wetted strip (ft)
sg	Specific gravity of the chemical concentrate
t_f	Specific tank flow rate for a given diameter and flux
T_a	Irrigation application time required during the peak use period (h/d)
T_r	Peak-use period transpiration ratio
T_R	Seasonal transpiration ratio
TDH	Total dynamic head (ft)
TDR	Temperature discharge ratio
v	Velocity of flow in the pipe (ft/s)
V_i	Gross seasonal volume of irrigation water required (acre-ft)
V_s	System coefficient of manufacturing variation
$V^2/2g$	Velocity head: the energy head from the velocity of flow (ft)
W_s	Residual stored moisture from off-season precipitation (ft)
WHC	Water-holding capacity of the soil (in/ft)
WS_r	Water supply rate, gal/min
x	Emitter discharge exponent
x_l	Any position along the length
x_{ce}	Distance from the closed end (ft)

x_{ce}/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 (%)
Y_{tl}	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)
v	Kinematic viscosity of water (ft^2/s)

Appendix B Equations

7–1	$Ca^{++} + 2Cl^{-} = CaCl_2$
7–2	$Ca^{++} + SO_4^{--} = CaSO_4$
7–3	$Ca^{++} + 2HCO_3^{-} = CaCO_3\ (ppt) + H_2O + CO_2\ (gas)$
7–4	$pH_C = (pK_d - pk_s) + p(Ca) + p(HCO_3) + p(ACF)$
7–5	$q_f = \frac{F_r A}{F_c \times T \times H_r}$
7–6	$F_c = \frac{KF_r}{H_r d_i}$
7–7	$C_t = \frac{KF_r A}{F_c}$
7–8	$P_w = \frac{eS_e S_w}{S_p S_r} \times 100$
7–9	$P_w = \frac{eS'_e (S'_e + S_w)}{2(S_p S_r)} \times 100$
7–10	$P_w = \frac{e\left[A_s + (.5S'_e \times P_S)\right]}{S_p S_r} \times 100$
7–11	$F_{mn} = (MAD)(WHC)(RZD)(P_w)$
7–12a	$ET_c = ET_o \times K_c$
7–12b	$ET_s = \sum_{Planting}^{Harvest} K_c ET_o$

7–13	$F_n = ET_c I_{fc}$
7–14	$EU = 100\left(1.0 - \frac{1.27CV}{\sqrt{e}}\right)\frac{q_n}{q_a} \times 100$
7–15a	$F_g = \frac{(F_n T_r)}{\left(\frac{EU}{100}\right)}$
7–15b	$F_g = \frac{F_n}{\frac{EU}{100} \times (1 - LR_t)}$
7–16	$F_{\left(\frac{gp}{d}\right)} = K\left[\frac{S_p S_r F_g}{I_f}\right]$
7–17	$F_{(an)} = (ET_s - R_e - W_s)$
7–18	$E_s = EU$
7–19	$E_s = \frac{EU}{T_R(1.0 - LR_t)}$
7–20	$F_{sg} = \frac{F_{an}}{E_s(1 - LR_t)}$
7–21	$V_i = \frac{F_{sg}(A)}{K(1 - LR)\frac{E_s}{100}}$
7–22	$F'_c = \frac{\text{Salt tolerance of crop}(EC_t)}{\text{Electrical conductive of irrigation water}(EC_w)}$
7–23	$L_r = \frac{0.1794}{F'c^{3.0417}}$
7–24	$q = K_d (h)^x$

7–25	$l_e = \frac{\pi h g d^4}{98.6 q(\upsilon)}$
7–26	$q = 187 a c_q \sqrt{2gh}$
7–27	$q = 187 a c_q \sqrt{2g(h - h')}$
7–28	$h' = \frac{h}{1 + m^2}$
7–29	$q = 187\, a c_q \sqrt{2g}\, h^{0.4}$
7–30	$q = 187\, a c_q \sqrt{2g}\, h^x$
7–31	$q = 187\, a c_q \sqrt{2g} \left(\frac{h}{m'}\right)^{0.7}$
7–32	$q = 187 a c_q \sqrt{2g \frac{h}{m'}}$
7–33	$CV = \frac{S}{\bar{q}} = \frac{\frac{\sqrt{q_1^2 + q_2^2 \ldots + q_n^2 - n\,(\bar{q})^2}}{\sqrt{n-1}}}{\bar{q}}$
7–34	$CV_s = \frac{CV}{\sqrt{e'}}$
7–35	$F_e = Kb(D_i)^{-1.86}$
7–36	$x = \frac{\log\left(\frac{q_1}{q_2}\right)}{\log\left(\frac{h_1}{h_2}\right)}$

7–37	$T_a = \frac{F_{\left(\frac{gp}{d}\right)}}{e\left(q_a\right)}$
7–38	$h_a = \left(\frac{q_a}{k_d}\right)^{\frac{1}{x}}$
7–39	$EU = 100\left(\frac{q_n'}{q_a'}\right)$
7–40a	$EU = 100\left(1.0 - 1.27\frac{CV}{\sqrt{e'}}\right)\frac{q_n}{q_a}$
7–40b	$EU = 100\left(1.0 - 1.27CV_s\right)\frac{q_n}{q_a}$
7–41	$\Delta H_s = 2.50\left(h_a - h_n\right)$
7–42a	$Q_s = 726\frac{A\ e\ \left(q_a\right)}{N\ S_p S_r}$
7–42b	$Q_s = 726\frac{A\ \left(q_a\right)}{N\ S_e S_l}$
7–42c	$Q_s = 726\frac{A\ e\ \left(q_a\right)}{N\ S_p}$
7–43	$O_t = 5430\left(\frac{V_i}{Q_s}\right)$
7–44	$q_n = q_a\left(\frac{h_n}{h_a}\right)^x$
7–45	$h_n = \left(H_m - \Delta H_m - \Delta h\right)$

7–46	$I_n = 1.604\left(\frac{EU}{100}\right)\left(\frac{eq_a}{S_p S_r}\right)$
7–47	$q_c = \frac{0.006CQ_s}{csg}$
7–48	$h_f = 10.5\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} L$
7–49a	$h_f = 0.00133 \frac{Q^{1.75}}{L\ D^{4.75}}$
7–49b	$h_f = 0.001 \frac{Q^{1.83}}{D^{4.83}} L$
7–50	$h_e = K_f \frac{V_2}{2g}$
7–51	$L' = L \frac{(S_e + f_e)}{S_e}$
7–52	$h_f = F\, h_{f\,no\ outlets}$
7–53	$h_{fx} = F\, h_f \left(\frac{X}{L}\right)^K$
7–54	$V_a = K \frac{q}{D^2}$
7–55	$PW_r = \left[\frac{(1+r)^n - (1+i)^n}{(1-r) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right]$
7–56	$EAE_{(r)} = \left[\frac{(1+r)^n - (1+i)^n}{(1+r) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n - 1}\right]$
7–57	$CRF = \frac{i(1+i)}{(1+i)^n - 1}$

7–58	$C_{whp} = \dfrac{(O_t)(P_{uc})(EAE_{(r)})}{\left[\left(\dfrac{BHP}{E_p}\right)\left(P_u'\right)\right]}$
7–59	$A_f = \dfrac{0.001C_{whp}}{(CRF)(P_c)}$
7–60	$Q_s' = A_f Q_s'$
7–61	$(H_{fe})_m = \sum_1^m h_f \Delta El$
7–62	$L_s = \dfrac{\Delta H}{h_{fs} - h_{fl}}$
7–63	$q_L = \dfrac{1}{S_e} \times \dfrac{q_a}{60} = \dfrac{n_c q_a}{60}$
7–64a	$h_l = h_a + 0.75 h_{fp}\left[z^K + (1-z)^K\right] - \left(\dfrac{\Delta E}{2}\right)(2z-1)$
7–64b	$h_l = h_a + 0.75 h_{fp}(0.5)^K = h_a + 0.11 h_{fp}$
7–64c	$h_l = h_a + \dfrac{3h_f}{4} + \dfrac{\Delta El}{2}$
7–65a	$h_c = h_a - \left(\dfrac{h_f}{4} + \dfrac{\Delta El}{2}\right)$
7–65b	$h_c = h_l - (h_f + \Delta El)$
7–66a	$(h_f)_b = (h_f)_a \left(\dfrac{L_b}{L_a}\right)^K$
7–66b	$L_b \cong L_a \left[\dfrac{(h_f)_b}{(h_f)_a}\right]^k$

7–67	$Y = \left(F \frac{\Delta E}{h_f}\right)^K$
7–68	$\frac{\Delta E}{h_f} - 0.36 \left[\frac{\Delta E}{h_f}\right]^{K1} = (z)^{K2} - (1-z)^{K2}$
7–69	$\Delta h = \Delta E(1-z) + h_f (1-z)^K$
7–70	$\Delta h_c = \Delta E(Y) - h_f (Y)^K$
7–71	$\Delta h = \Delta h_c = \Delta E\, h_f$
7–72	$(\Delta H_m)_A = \Delta H_s - \Delta h'$
7–73	$L_p = \left[(n_p) - 1\right] S_r$
7–74	$L_m = \left(n_r - \frac{1}{2}\right) S_r$
7–75a	$H_m = h_l + \Delta Hm'$
7–75b	$H_m = h_a + \Delta h' + \Delta H_m'$
7–76	$\Delta Hm' = MH_f + 0.5 \times \Delta E1$
7–77	$(H_f)_2 = \left(\frac{L_2}{L_1}\right)\left(\frac{F_s}{F_s}\right)_2 \left(\frac{q_2}{q_1}\right)^{1.8} (H_f)^1$
7–78	$N_t = \frac{Q_s}{t_f}$
7–79	$D_f = 0.5 D_d \sqrt{N_d}$
7–80	$D_v = K_v \frac{\sqrt{Q_v}}{0.25}$

(P_v)

7–81 $$L_d = \left(\frac{q_d - q_{(d-1)}}{q_m}\right) L_m$$

7–82 $$F2_{a_w} = \frac{1.604\left(e \times q'_a \times T_a\right)}{A_w}$$

7–83 $$F'_a = \frac{1.604\left(e \times q'_a \times T_a\right)}{\left(S^p \times S_r\right)}$$

7–84 $$F'_{(gp/d)} = \frac{1.604\left(e \times q'_a \times T_a\right)}{I_f}$$

7–85 $$EU'_m = 100 \frac{q'_n}{q'_a}$$

7–86 $$ERF = \left[\frac{\left[\text{average MLIP} + \left(1.5 \text{ minimum MLIP}\right)\right]}{25}\right] \left(\text{average MLIP}\right)$$

7–87 $$ERF = \frac{(\text{minimum MLIP})^x}{\text{average MLIP}}$$

7–88 $$EU' = \left(ERF \times EU_m'\right)$$

7–89 $$F_n = \left(F'_n - R'_e\right)$$

7–90 $$PE_{lq} = \frac{EU'}{T_R\left(1.0 - LR_t\right)}$$

7–91 $$PE_{lq} = EU'$$

7–92 $$E_{lq} = 100 \frac{G}{F2_{(gp/d)}}$$