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**Natural
Resources
Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

# Chapter 1

# Introduction: Ecological and Physical Considerations for Stream Projects

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**Cover photos:** *Top*—Restoring stream habitat is a balance between water, earth materials, plants and animals, and the goals and objectives of the restoration.

*Bottom*—The ecology of the stream must be characterized for the current and future conditions, with remedial measures in place.

## Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

# Chapter 1

# Introduction: Ecological and Physical Considerations for Stream Projects

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# Introduction: Ecological and Physical Considerations for Stream Projects

## 654.0100 Purpose

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) National Engineering Handbook (NEH), Part 654, Stream Restoration Design provides guidance for multidisciplinary teams who are planning and designing projects to improve streams and their functions. Specific project goals may include flood control, sediment control, improving drainage, stabilizing banks, improving fish habitat, and restoring the ecological functions and processes of a stream and its flood plain.

Many approaches and techniques can be used to reach these goals, but a good understanding of the living and nonliving components of the stream ecosystem, its watershed, how they interact and affect each other, and the timeframes over which stream processes occur will improve the chances of success.

This chapter provides an overview of processes important to stream corridors and their ecosystems. Stream corridors include the stream channel, riparian zone, and flood plains (level areas near the channel, formed by the stream and flooded during moderate-to-high flow events). Stream corridor features are shaped by the forces of flowing water, which depend on local topography and geological characteristics. Stream corridors are also influenced by the cumulative effects of upland and upstream activities and practices, including agricultural production, forestry, recreation, other land uses, or urban development.

The chemical and biological processes that occur within stream systems are intricate and involve numerous interactions, linkages, and feedback loops. Accordingly, this chapter presents a brief overview of current knowledge regarding stream ecosystem processes and functions important to consider when designing stream improvements. For a more comprehensive treatment of these processes, readers may wish to review one of several references, including Stream Corridor Restoration: Principles, Processes, and Practices, developed by the Federal Interagency Stream Restoration Working Group (FISRWG) (1998).

## 654.0101 Introduction

In 1998, water quality in at least 40 percent (by length) of assessed streams in the United States was listed as impaired by the U.S. Environmental Protection Agency (EPA) (EPA 2000). Reports of the status of freshwater species are also dismal: about a fourth of native freshwater fish species (Williams et al. 1989; Stein and Flack 1997), a half of native freshwater mussel species (Williams et al. 1993), a fourth of native amphibians (Stein and Flack 1997), and a third of native crayfish species (Taylor et al. 1996) are imperiled or extinct. Aquatic species are not only valued natural resources—they are indicators of water quality. The continued rapid decline in aquatic biodiversity (Ricciardi and Rasmussen 1999) places great responsibility on those who work in streams.

## 654.0102 Restoration, rehabilitation, and reclamation

Some methods of determining objectives have pitfalls. It is probably not possible to fully restore all the functions and values of a stream to a specified original condition, or, more accurately, a condition at a particular point in time. This ignores how streams form and how they maintain themselves. Taking a stream backwards is contradictory to what is known about modern ecology because it implies some static climax state that a natural system tends towards, both elastically and linearly.

Some stream work is clearly repaired in nature, which may be to fix simple erosion problems. Even simple erosion control projects on streams should be designed to maintain or improve ecological functions and values. Repairs can become little more than temporary bandages to treat what is actually a larger problem. This may result in wasted time and resources, if the problems are systemic in nature and reflect more serious imbalances between the stream, its riparian area and corridor, and its watershed.

The following terms are sometimes used interchangeably with regard to working on streams to restore specific functions and values (FISRWG 1998):

- **Restoration** is the reestablishment of the structure and function of ecosystems (National Research Council 1992). Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. Implicit in this definition is that ecosystems are naturally dynamic. It is, therefore, not possible to re-create a system exactly. The restoration process reestablishes the general structure; function; and dynamic, but self-sustaining, behavior of the ecosystem.
- **Rehabilitation** is making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat (Dunster and Dunster 1996). Rehabilitation does not necessarily reestablish the predisturbance condition, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic. Most of the stream projects that NRCS has been involved with are rehabilitations.
- **Reclamation** is a series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery (Dunster and Dunster 1996). The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose, such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses. Restoration differs from rehabilitation and reclamation in that restoration is a holistic process not achieved through the isolated manipulation of individual elements. While restoration aims to return an ecosystem to a former natural condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose (National Research Council 1992).

It may be difficult or impossible to restore a stream to a particular historical condition due to changes in watershed land use and human population, as well as slight to major climatic changes. It may also be difficult or impossible to adequately describe the desired historical condition, both in terms of the stream's pattern and physical characteristics, as well as its physical, biological, and chemical attributes—its ecology. For the purposes of this document, the planned stream actions, for which designs are needed, may be termed restoration, rehabilitation, or reclamation, in the context of the plan's objectives and goals. It is also possible that the plan may create or re-create some functions and values that are new to the stream, or are logical, given historical watershed changes. Most stream work done by the NRCS may be best termed rehabilitation, except where efforts are clearly focused on restoring a range of ecological functions and values to a defined historical condition.

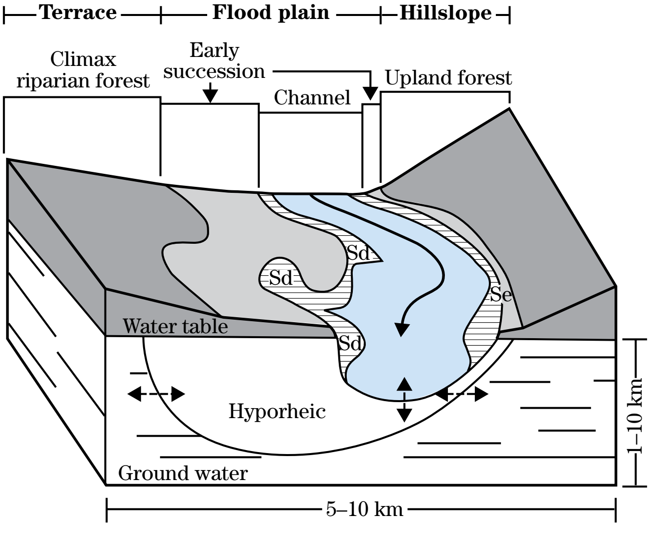
Restoration actions may be passive, simply to remove or attenuate chronic disturbances. Restoration may also be active, to intervene and install measures that are specifically designed to repair damages to the ecological structure and functions of stream corridors.

## 654.0103 Understanding stream corridor dynamics

Stream corridors are complex and dynamic. Natural or minimally altered stream corridors tend to be physically heterogeneous regardless of their size, with diverse patterns and types of habitats. Larger river corridors show more variation and complexity lateral to the channel, while smaller stream corridors tend to vary more longitudinally. Fluxes of energy, water, and materials throughout the stream corridor system create a dynamic three-dimensional (length, width, depth) mosaic of habitats and physical features (fig. 1–1 (modified from Stanford and Ward 1992)).

Length, width, and depth may also be identified as longitudinal, lateral, and vertical dimensions. These physical features change with time and contribute to the high level of biological diversity typical of stream corridors. The interactions occurring among the different elements of stream corridors are extensive for many of the plant and animal species that inhabit or use them. For example, bats living in the riparian zone eat aquatic insects living in the stream, while stream fishes eat both aquatic and terrestrial insects that thrive in riparian vegetation.

**Figure 1–1** Cross-sectional view of generalized stream corridor showing three spatial dimensions in which stream corridor habitats are formed through time



Biota (the flora and fauna of a region) may reside in all habitats (riparian, inchannel, hyporheic, and/or ground water zone). The hyporheic zone is the saturated interstitial area beneath the streambed and in the streambanks, where surface and subsurface waters mix (fig. 1–1). Sd designates sediment deposition sites and Se is a site of bank erosion.

Human activities in stream corridors often simplify physical structure (by removing riparian vegetation). Human activities also may fragment connections, such as between the stream and its flood plain, preventing or diminishing natural processes important to many species. Projects designed to restore or maintain the inherent complexities of stream corridors, ecological linkages, and their physical connections are one solution to arrest the decline of aquatic and riparian species and to improve the Nation's water quality. Of course, projects can also address degraded/altered water quality, flow alteration, habitat enhancement, and other problems confronting stream ecosystems.

### (a) Science and stream project design

The complex physical, biological, and social nature of stream corridors creates a challenge to professionals responsible for improving stream functions and conditions. Ward et al. (2001) suggested that scientists often misinterpret stream corridor processes because they usually study regulated systems—those already cleared of wood, dammed, channelized, revetmented, leveed or constrained by other types of hard structures. Systems with more intact natural flow regimes are characterized by high levels of heterogeneity, both in space and in time. From a human perspective, they are also less well behaved, less predictable, and increasingly rare in today's landscapes.

Much additional work is needed to understand the physical and biological processes typical of natural fluvial systems, or even partially altered systems, especially those with braided river channels. Scientifically validated models that help predict the physical behavior of stream systems are based mostly on single-thread meandering channels (Shields, Copeland, et al.

2003). Recent studies in stream ecology emphasize the importance of links between stream channels, riparian areas, flood plains, and hyporheic zones (Gregory et al. 1991; Naiman et al. 1992; National Research Council 1992; White 1993; Brookes, Knight, and Shields 1996; Huggenberger et al. 1998; Molles et al. 1998; National Research Council 2002).

Stream project designers rely on science and professional judgment as they develop stream improvement plans. Because professional judgment is often subjective, and applied experience may be limited, stream improvement project designs may become controversial when different disciplines are involved. Stream corridor projects that integrate the disciplines of fluvial geomorphology, hydrology, aquatic and riparian ecology, and hydraulic and geotechnical engineering are more effective at meeting multiple objectives that accommodate both economic and ecological considerations.

## (b) Channel form and fluvial processes: Understanding stream corridor dynamics

Older science regarding physical aspects of streams contains many interesting observations about stream form. Earlier workers argued that form variables like the bed slope, channel width-to-depth ratio, meander wavelength, and bed-material size were related by functional relationships. Furthermore, they argued that disturbed channels (channelized streams) would not conform to these relationships, but would experience adjustment through erosion and deposition that eventually would return them to the appropriate (stable) form. Form studies naturally led to an effort to classify stream reaches based on form variables, and stream classification systems have been developed, ranging from very simple schemes with three or four categories (Shields and Milhous 1992) to those with several dozen categories (Rosgen 1996). More recent science has focused on physical, chemical, and biological processes that produce stream forms.

Since processes are driven by the dynamic variables of climate, tectonics, biological processes (plant succession, die-off, human population growth), the focus on processes has prompted reconsideration of the idea that without human intervention, fluvial systems will tend to approach an equilibrium or stable form. Although earlier workers knew the importance of processes in controlling forms and correctly identified most of the key processes (Leopold, Wolman, and Miller 1964), they often lacked the technology to monitor processes and develop mathematical descriptions. Recent advances allow scientists to collect large quantities of directly measured or remotely sensed data and use the data to build and revise their computational models. Much work remains to be done in understanding and predicting the behavior of stream ecosystems, but recent advances indicate that the best design work is usually based on general, analytical process-based approaches, rather than more subjective or site-specific empiricism.

## (c) Using models to understand and manage complex systems

Models are descriptions of systems, which are collections of interrelated objects. An object is some elemental unit on which observations can be made, but whose internal structure either does not exist or is ignored (Haefner 1996). There are many types of models. Conceptual models describe the objects and relationships either with words or diagrams. Physical models, like plaster models of a watershed, are three-dimensional representations, usually at some relevant scale. Formal mathematical models represent objects and interactions quantitatively with equations and are typically implemented on computers.

Conceptual models are valuable frameworks for designing stream projects because they identify important components of the ecosystem and the processes that maintain it (Vannote et al. 1980; Schlosser 1987; Simon 1989). Project design teams can use these models to develop a common understanding of the system and to determine actions that are more likely to result in desired outcomes.

### Applications of models

Model realism, precision, and generality should be considered when selecting a model (Levins 1966). Model realism and generality are important when using models as frameworks for understanding the stream (Haefner 1996). Models selected for predicting the outcome of a project (change in channel dimensions, change in fish abundance or community structure) must be precise and realistic, but they do not need to generally apply to all systems. Defense of a model should include explanation of basic algorithms and calibration, as well as an independent validation. Models may not perform well in design of restoration or management actions at a site if they:

- fail to consider important components or processes within the system
- represent critical relationships too simplistically
- substitute professional judgment because data from the system of interest are not available
- use data from recent observations to project responses over decades to centuries
- address only part of the system or part of the life histories of the aquatic and riparian organisms
- do not account for disturbances and unpredictable processes that are important in the system
- do not account for site-specific geological conditions, or assume that they are constant in different watersheds

A good model produces results for existing data or observable conditions. Such a model may provide an expected result for a restored or altered condition, subject to model and data limitations. Remember that no perfect model exists, but models may show the relative differences or directions of changes in a stream ecosystem when alternative treatments or systems are considered.

## 654.0104 Fluvial systems

### (a) Watersheds

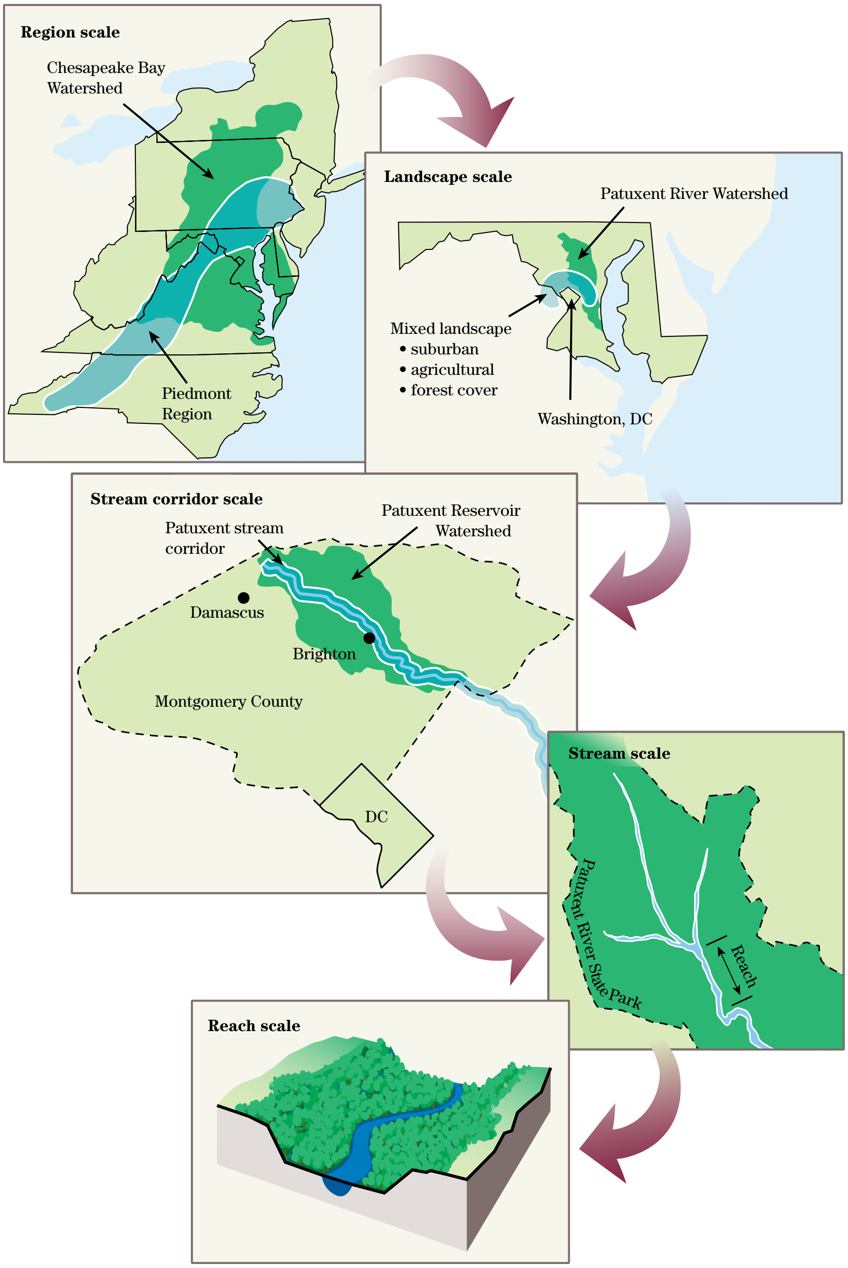
A watershed is a topographically bounded area of land that captures precipitation, filters and stores water, and regulates its release through a channel network into a lake, another watershed, or an estuary and the ocean. Watersheds are nested within one another, with larger watersheds composed of many smaller tributary watersheds, and these smaller tributaries drained by even smaller intermittent channels, ephemeral channels and rills. Watersheds are comprised of a mosaic of soil types, geomorphic features, vegetation, and land uses. If a watershed is divided into uplands and stream corridors, the uplands comprise most of its area (in most basins). Upland features control the quantity and timing of water and materials that make their way to the stream corridor. The environmental conditions of the stream corridor (such as water quantity and quality, riparian function, and fish habitat) are, therefore, linked to the entire watershed, and these linkages go both ways. For example, animals living primarily in upland habitat frequently rely on stream corridors for movement, food, cover, and water. Recent studies have also shown that marine derived nutrients carried up stream corridors in the tissues of salmon enhance the growth and survival of adjacent forest stands from which large wood in those rivers and streams originates (Helfield and Naiman 2003). Although stream project designers may have little or no control over how a watershed is managed, their plans and designs still should consider the past, present, and future status of watershed land use and historical watershed conditions.

#### Landscape consideration of watersheds: spatial scales

A landscape perspective is important when managing natural resources. The spatial structure of landscapes influences ecological and physical processes such as energy flow, material transport, and species dispersal within a landscape. These processes occur in all three spatial dimensions and over time within a watershed or river basin (Stanford and Ward 1992; Beechie and Bolton 1999).

Resource managers consider spatial structure of landscapes at very large scales (to analyze satellite imagery of large sectors of the Earth's surface) and at much smaller scales (to manage habitat in a stream reach), depending on the issue at hand (fig. 1–2 (FISRWG 1998)). Regardless of project scope, some consideration should be given to all scales. For instance, focusing only on the reach scale may overlook important issues that will dramatically impact the project. While many NRCS projects are applied on relatively short reaches, the stream's watershed should always be considered.

**Figure 1–2** Spatial scales surrounding stream corridor ecosystems

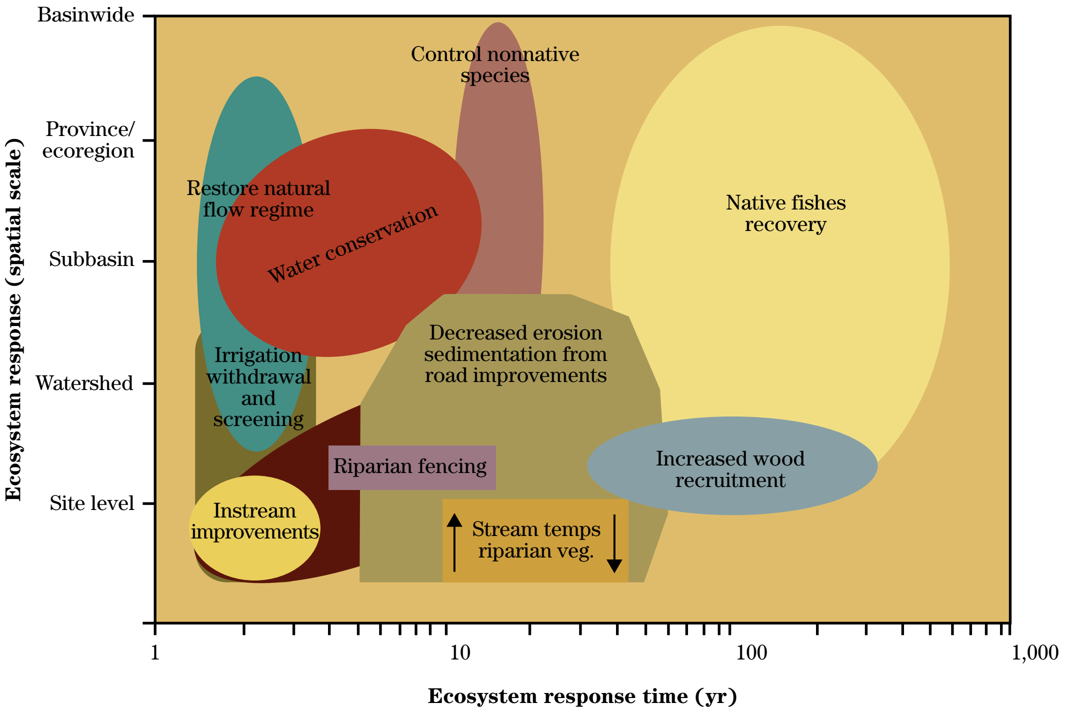


Rivers and streams, and the corridors through which they flow, may be considered long ribbons of aquatic habitat or riverscapes (Fausch et al. 2002). Riverscapes are also important to terrestrial plants and animals because stream corridors provide a transition between wet and dry habitats. Habitat is the place where an organism lives, and includes the range of environmental conditions (physical, chemical, and biological) it needs to grow and reproduce (Odum 1971). The spatial and temporal scales of a habitat are not fixed, but rather determined by the physical and biological processes that create it, the range of activities (home range) of the organism, its interactions with the biotic community, and the population dynamics of the species.

The habitat of a large or relatively mobile organism (Pacific salmon) contains the smaller scale habitats of smaller, or less mobile, organisms (aquatic insects and crayfish). This kind of organization implies a hierarchy of habitats and interactions that are formed by processes and nested in space. How long it takes for these multiple habitats to respond to stream restoration depends on the project's nature and scope and the dynamics of its landscape (fig. 1–3). Species responses to habitat modifications depend not only on the actual site work but also on the ecology of the surrounding watershed.

A hierarchical approach to stream design identifies the main spatial scale at which each ecosystem component influences the characteristics of the stream, but it does not imply that components at lower hierarchical levels are less important than those at higher levels. In fact, the connectivity of the stream environment involves feedback mechanisms by which smaller scale components may influence larger scale patterns and processes (DeAngelis, Post, and Travis 1986; Naiman 1988). Therefore, an effective stream restoration plan should consider factors affecting stream corridor processes at different spatial scales, from landscape to watershed to microhabitat. The plan should also consider factors that influence long-term population status and dynamics of aquatic species and the community of species with which they interact. This type of biological information is often available from researchers at

**Figure 1–3** Spatial and temporal responses of ecosystem conditions to stream and watershed restoration actions



local universities or biologists of local fish and wildlife agencies. Focusing exclusively on maintaining local fish habitat by protecting or enhancing selected stream reaches may be ineffective in the long term because effects may be negated by changes in the stream system that occur at larger scales (Frissell and Nawa 1992).

### Watersheds, stream corridors, and the dimension of time

Configurations of stream corridors change over time, as does the capacity of a channel to convey and retain water. Over geologic time all streams and their flood plains are active, often reworking entire valley floors by eroding and depositing sediments within their channels and the adjacent flood-prone areas. During smaller timeframes, pools within stream reaches are formed and maintained by erosion, and organic deposits and riffles are formed by deposition of sediments. Long-term trends in fluvial variables can be obscured by fluctuations over shorter timeframes. Stream projects are typically designed based on conditions that prevail over many decades, and they usually have projected lifetimes that do not exceed 50 to 100 years. Some geomorphologists have suggested that fluvial systems tend to reach a physical equilibrium or stability over periods that range from decades to centuries, and have termed this state "dynamic metastable equilibrium" (Schumm 1977).

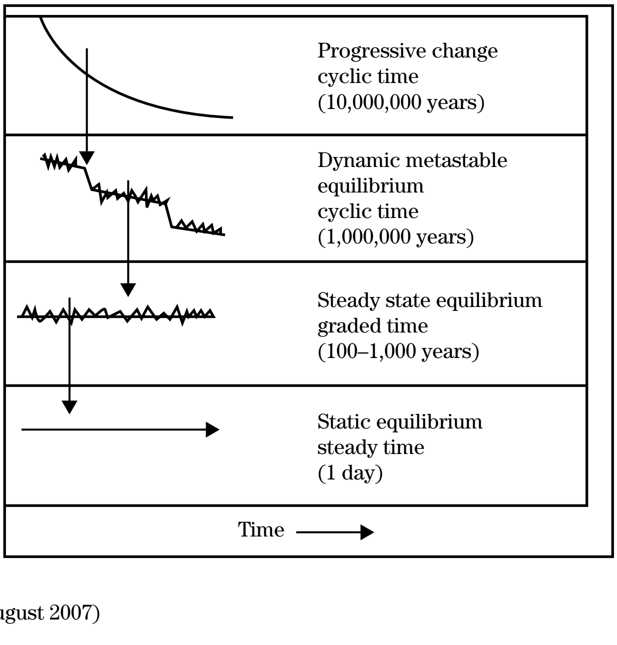
According to this theory, the physical characteristics of channels remain relatively constant during the equilibrium periods, and undergo rapid changes during short episodes that occur when the system exceeds some internal threshold (fig. 1–4). During periods of equilibrium, the channel is adjusted to inputs of water and sediment so that average channel width, depth, slope, and sediment grain size change little for any given reach. The channel transports the same amount of sediment that it receives and experiences no net erosion or deposition, although erosion or deposition may occur at smaller spatial scales, such as pool and riffle habitats. This concept of a dynamic metastable equilibrium has been useful in analyzing the response of stream channels to changes in the watershed, but it may not be valid for all streams. Nevertheless, designers attempt to select channel geometries (width, depth, slope, meander wavelength, bed and bank roughness, bed sediment size) that correspond to a stable condition defined by empirical or theoretical equations. At best, these constructed geometries will be appropriate during the periods of equilibrium. However, structural measures may be necessary to prevent changes across a threshold. Less intervention may be required if the stream is allowed to move in its flood plain, or if sediment production from the watershed can be managed.

### Movement of water

Water that enters the watershed in the form of precipitation moves from the land into the stream channel as surface runoff or, if it infiltrates, enters as subsurface and ground water flow. Based on its pathways to the channel, streamflow is classified as stormflow or baseflow. Stormflow is the water from precipitation that reaches the channel over a short period of time (during and immediately after a storm event) through surface or subsurface routes. Baseflow is the water that percolates slowly through the ground before reaching the channel, where it maintains flow during periods of little or no precipitation.

Variability of flow is a key factor influencing the biotic and abiotic processes that determine the structure and dynamics of stream ecosystems (Poff and Ward 1990; Covich 1993). The path that water takes through a watershed determines the quantity of sediment and dissolved matter that reaches the stream. In general, the

**Figure 1–4** Concepts of geomorphic equilibrium in stream corridor systems



amount of sediment suspended in the water column is greatest in small channels, gullies, and rills, intermediate in sheet flow, and lowest in ground water. Nutrient levels in water are often reduced as subsurface runoff percolates through riparian root zones. Once in the stream, nutrient concentrations are influenced by structures and processes that retard flow or promote retention, including vegetation and large wood within the channel, exchange with the hyporheic zone, or slowing of streamflow in meanders, sloughs, and flood plain depressions. In general, deposition and processing of nutrients are increased by longer flow retention time. Flood control systems designed to increase flow velocities and reduce net retention time of flood waters can greatly alter nutrient dynamics in stream corridor ecosystems.

### Movement of inorganic sediments

Watersheds transport sediment, as well as water, but sediment transport usually varies as a function of discharge. As a result, changes in discharge magnitude and duration (downstream of a flood control dam) throughout the watershed magnify changes in sediment discharge. Alluvial channels (those with beds and banks made of materials readily transported by the stream, in contrast to threshold channels that are controlled by bedrock outcrops or materials too large for the stream to frequently transport) constantly adjust their geometry in response to the sediment load they receive.

Sediments range in size from clay particles, only a few microns in diameter, to large boulders, but a given stream is typically dominated by a smaller range of sediment sizes (sand to gravel or just fine sand). The types of stream organisms reflect the quantity and size distribution of sediments that move along or lie on the bed of the stream corridor. Aquatic organisms are quite sensitive to the size distribution of sediments (Shields and Milhous 1992). The frequency of bed-material movement and sediment-size distribution controls the size of microhabitats provided by interstitial spaces of bed substrates. Those streambeds dominated by uniform and small size particles (fine sediments) naturally sustain fewer species of aquatic insects (Benke et al. 1984).

Typically, species-rich stream substrates have particles of a wide range of sizes coarser than sand. The resulting high porosity of the streambed allows exchange of well-oxygenated water in the channel and within the hyporheic zone. This component of stream corridors is yet another zone of complex gradients and transitory boundaries over space and time.

### Movement of organic material

Movement of organic material within a stream corridor system also occurs in four dimensions. The timing, quality, and quantity of organic matter transport through a stream system are related to streamside vegetation, channel complexity, aquatic food web dynamics, light intensity (from the sun), seasonal fluctuations in flow, and all of the aforementioned physical processes that influence the movement of water and sediments. Organic material includes parts of trees and shrubs, insects, nutrients in surface runoff, and aquatic organisms.

In forested landscapes, trees in upland areas become structural elements of stream corridors when carried to channels by landslides. In most landscapes, trees and/or shrubs border stream channels, even if the rest of the watershed is too arid or too developed to support woody species. Riparian trees fall into streams and flood plains during windstorms, floods, or bank sloughing and mass failures. Trees and other woody material are critical elements of aquatic ecosystems, affecting both the physical and ecological structure and function of stream corridors (Gregory, Boyer, and Gurnell 2003). The mobility of wood in streams and rivers is highly variable from site to site, depending on the size, slope, and configuration of the channel, as well as the characters of the wood (especially its size, morphology, density, decay rate, and extent to which it is lodged in the channel). Wood accumulations or single logs in unaltered, low-order streams may stay in place for decades or centuries, creating stable step-pool habitats.

Wood in large river channels often shifts with seasonal flows. This can cause considerable concern for river managers who are responsible for ensuring the safety of recreational users or for minimizing risks to infrastructure such as bridges. Still, the growing recognition that large wood is an important component in stream systems has led researchers and managers worldwide to develop innovative techniques for adding large wood to streams and rivers (NEH654 TS14J; Reich, Kershner, and Wildman 2003). Because woody debris can alter the flow path and shape of stream systems, programs exist to both remove and to retain wood in the stream.

# 654.0105 Channels

## (a) Describing channels

The cross section of an average stream channel can vary greatly depending on water flow, amount of sediment carried by the water, and the geology of the terrain. The dimensions of a channel cross section between the sloped banks define the active channel and determine the amount of water that can pass through without spilling over the banks (fig. 1–5). The deepest part of the channel is referred to as the thalweg.

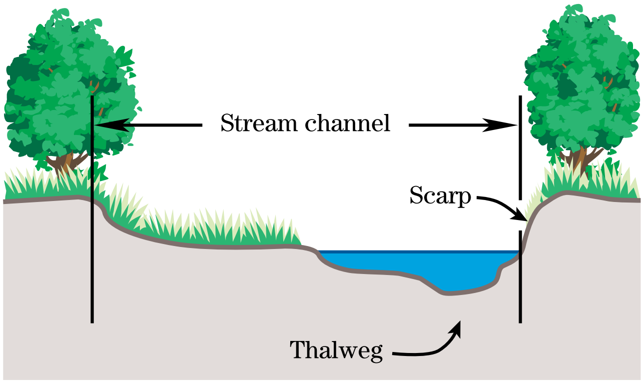
Channel slope is the average slope of the longitudinal thalweg profile. Flow velocity and stream power are proportional to the slope. Because these variables determine the rates of erosion, sediment transport and deposition, channel slope is an important controlling factor in channel form and pattern.

The form of a channel changes from its headwaters to lower elevations. In the steeper terrain of the headwaters, stream channels tend to be single and relatively straight. Channels of intermediate slope tend to maintain a single channel, but with increased sinuosity (curvature). Once in the depositional, flat slope of a watershed's lowlands, channels tend to develop multiple threads (or channels) and very high sinuosity. Multiple thread streams are further divided into braided and anastomosed streams. While static, braided streams are not often observed, they usually are formed in response to erodible banks, high bed-material sediment load, and rapid and frequent variations in stream discharge. The multiple channels of braided streams tend to be shallow and wide. In contrast, the multiple channels of anastomosed streams tend to be narrow and deep, because their banks are typically cohesive sediments. Anastomosed channels are often found on alluvial fans. While the description is a generalization, it should be noted that large parts of the country such as the Midwest have very flat channels, and these channels may either steepen or remain flat with distance downstream.

Natural stream channels are typically never totally straight and display different amounts of curvature or sinuosity. The sinuosity of a stream reach is calculated by dividing channel length by valley length. Sinuosity can also be calculated by dividing valley slope by stream slope. The degree of meandering is low if the sinuosity is less than 1.2, appreciable for sinuosities of 1.2 to 1.5, and high for sinuosities above 1.5. Sinuosity is related to both streamflow and gradient. In general, low to moderate levels of sinuosity are found in the headwaters, and these levels increase as the stream enters the flat and broad valleys downstream.

Independent of their form, stream channels are rarely uniform in depth and tend to have alternating, regularly spaced, deep (pool) and shallow (riffle) areas. Pools typically form where the thalweg approaches the outside bank of the channel at bends, whereas, riffles usually form between channel bends in the zone where the thalweg migrates from one side of the channel to the other. Streambed composition affects the pool and riffle characteristics, as well. Streams with coarse substrates, gravel to cobble-size particles, tend to have evenly spaced pools and riffles, to the extent that pool-to-pool distance is approximately five to seven times the width of the channel at bankfull discharge (the discharge that fills a stable alluvial channel up to the elevation of the active flood plain). In such systems, cobbles and large gravels accumulate in the riffle areas, while smaller particles tend to deposit in the pools. On the other end of the spectrum, streams with sand and silt-dominated substrates do not form true riffles due to the absence of coarse grain sizes. However, they still have evenly spaced pools connected by shallower runs or glides.

**Figure 1–5** Cross section of stream channel



For assessment and design, it is useful to categorize stream channels as threshold channels or alluvial channels. Threshold channels have beds and banks that are not easily mobilized by the stream or river flow, while alluvial channels are continuously or frequently reshaped by erosion and deposition. Alluvial channels are shaped constantly by their streamflow. Differentiating between these two types of channels is subjective, since almost all channels have mobile boundaries under extremely high flows. Alluvial channels may be preliminarily assessed with one dominant discharge, but are assessed under a range of expected flow conditions. Threshold channels are so called because the flow forces during a given discharge are at or below the level (threshold) needed to move particles on the channel bed or banks. Typically, threshold channel boundaries are assessed for mobility under design flow conditions. Threshold channels occur when there are bedrock outcrops, or when coarse boundary materials are remnants of earlier fluvial processes, such as glacial outwash. Threshold channels have beds and banks that are mobilized slowly by the streamflow or riverflow, provided there are no human-induced changes in the watershed and stream system.

In alluvial channels, there is a frequent exchange of channel boundary material with the flow. Meander migration in stable threshold channels might be a few feet or less annually, while in alluvial channels it could be many feet of movement in response to a single stormflow. The distinction between alluvial and threshold streams is addressed in more detail in NEH654.07.

## (b) Key physical variables

Stream channels require up to 13 variables for a complete physical description, but only three governing equations are known, and only about six of the variables are fixed by site conditions (table 1–1 (Hey 1982, 1988)). See FISRWG 1998 for a fuller description of the meaning of each of the variables. Since there are more unknowns than equations, channels are indeterminate systems. For threshold channels, most variables are fixed by site conditions or by the choice of the designer, but alluvial channels can adjust their geometry in several dimensions. Existing models are not capable of accurately predicting long-term behavior of channels even when water and sediment in flows are specified.

**Table 1–1** Degrees of freedom and governing equations

| Type of channel | Governing equations | Fixed variables | Independent variables | Degrees of freedom | Dependent variables |
|---|---|---|---|---|---|
| Threshold, fixed bed, no sediment transport | Continuity, flow resistance | $S$, $W$, $d_m$, $\lambda$, $\Delta$, $p$, $z$ | $Q$, $D$, $D_r$, $D_l$ | 2 | $V$, $d$ |
| Planform and width are fixed, bed is mobile | Above, plus sediment transport | $W$, $d_m$, $\lambda$, $\Delta$, $p$, $z$ | $Q$, $Q_s$, $D$, $D_r$, $D_l$ | 3 | $V$, $d$, $S$ |
| Fully alluvial | Above equations, plus six additional process equations needed to render the system determinate, but these are generally not available | | $Q$, $Q_s$, $D$, $D_r$, $D_l$, $S_v$ | >3 | All but independent variables |

$V$ = mean flow velocity; $d$ = mean depth; $S$ = bed slope; $W$ = width; $d_m$ = maximum flow depth; $\lambda$ = bedform wavelength; $\Delta$ = bedform amplitude; $p$ = sinuosity; $z$ = meander arc length; $Q$ = water discharge; $Q_s$ = sediment discharge; $D$, $D_r$, $D_l$ = characteristic sizes of bed, right and left bank sediments, respectively; $S_v$ = valley slope.

Predicting the type of planform a channel will develop (straight, braided, or meandering) or the rate of lateral erosion of streambanks (meander migration) is difficult at best.

### (c) Using conceptual models to understand stream channel dynamics

Conceptual models often link structural properties of stream channels with critical processes that operate within them in a qualitative fashion. An example of a process based conceptual model is the incised channel evolution model (CEM) (Schumm, Harvey, and Watson 1984; Simon 1989), which describes changes in straightened channels that are undergoing headward incision. Presented in greater detail in NEH654.03, this conceptual model is based on observations of channels in watersheds undergoing systemwide disturbance.

Although the model does not allow prediction of the magnitude or rate of channel changes, it does link processes and allow qualitative prediction of outcomes (channel widening, progression of incision, and incision control options). The CEM is idealized, and any processes or conditions that are different than the fundamental conditions assumed in the model may alter the outcomes. For example, channels may change the trajectory or location of incision if boundary conditions are changed or pulses of sediment are supplied by incising tributaries. Another important feature of the CEM is that it allows resource managers to differentiate between local instabilities (erosion of the outside of a particular bend due to impinging flow) and systemwide instabilities (increased peak flows related to increases in impervious surfaces), which are much more complicated to control.

Conceptual models are widely used by stream ecologists, as well. Major conceptual models in stream ecology include the river continuum concept (Vannote et al. 1980), flood pulse concept (Junk, Bayley, and Sparks 1989), nutrient spiraling concept (Newbold et al. 1981), natural flow regime (Poff et al. 1997), patch dynamics concept (Townsend 1989), serial discontinuity concept (Ward and Stanford 1995b), and ecosystem perspectives of riparian zones (Gregory et al. 1991). Such models help organize ecological thinking about streams and rivers, much the same as the CEM helps hydrologists and geomorphologists understand the process of incision in stream channels.

As an example, the river continuum concept (RCC) suggests that the physical form of streams and rivers is generally predictable from headwaters to large flood plain rivers. In all these cases, the RCC provides a conceptual model that helps people think about how they expect the stream ecosystem to be structured and what processes are most likely to occur along the network from headwater streams to large rivers. Such conceptual models are useful in assessing stream degradation and setting restoration goals because they describe how physical habitats are related to aquatic community structure and the ecological processes that are important to them.

### (d) Using classification systems to describe channels

Although every stream is a unique combination of watershed characteristics, channel boundary conditions, and hydrologic and climatic regimes, people have long attempted to generalize their knowledge about streams by developing classification systems (Hawkes 1975; Bryce and Clarke 1996; Rosgen 1994; Frissell et al. 1986; Montgomery and Buffington 1993a, 1993b; Thorne 1997). Environmental classification systems are thoroughly reviewed by Zonneveld (1994) and stream classification systems by Kondolf (1995), Kondolf and Downs (1996), and USDA NRCS (2001c). Classification systems generalize field observations, facilitate communication, and identify dominant groups of processes. Classification systems are useful tools for communicating descriptive information since it saves time to simply state that a stream is type X, rather than specifying values for all of its component variables.

Overly simplistic use of categories can lead to misunderstandings and cookbook approaches, rather than an understanding of how a stream reach is functioning. Some workers have suggested that stream classification may be used to develop restoration prescriptions or to predict changes in morphology or ecology. Extremely simple classification systems include those based on flow habit (ephemeral, intermittent, perennial), planform (straight, braided, or meandering), or boundary mobility (threshold or alluvial). Others include physical variables (bed-material size, slope, sinuosity, channel width, valley shape) or biological characteristics (riparian vegetation, insect communities, or fish communities). Most stream classification systems are based on morphological or form variables (how streams look), rather than process variables (how streams behave, for example, widening or degrading). It is always easier to determine form, rather than process because processes act over time. Therefore, process determinations require sequential observations, historical data, or some surrogate, such as a space-for-time substitution. Unfortunately, fluvial systems are complex (threshold responses, variable responses, biological adaptation) and frequently changing (climate, streamflow, tectonic events, land use changes). It is difficult to accurately predict future stream behavior from current morphology.

Accordingly, a classification system alone should not be used for determining the type, location, and purpose of restoration activities (FISRWG 1998). Some have proposed the idea of a diagnostic or weight of evidence approach as an alternative to process models, evolution or conceptual models and classification systems (Ward and Trimble 2004).

## (e) Using mathematical models to predict channel responses

Quantitative predictions usually require a series of numerical calculations. Like most environmental systems, stream and watershed systems are complex, so the series of numerical calculations needed to make a prediction have been incorporated into a wide range of different models. The components of mathematical models are described in measurable units, and the relationships and processes within the models are represented by explicit mathematical formulas. Most complex mathematical models require specialized training in the scientific discipline that is being modeled (phytoplankton or sediment transport). Some complex mathematical models include user interfaces that ask specific questions and make it possible for an informed resource specialist to apply the model. Even in such cases, users of complex mathematical models should be aware of the context for which the model was developed, assumptions within the model, and data required to run the model. As a result, mathematical models are less popular for general application in stream project designs than broader conceptual models. However, the quantitative projections and predictions of mathematical models can greatly enhance the design of a project if the appropriate expertise is available to the design team.

Quantitative models of streams have become quite complex, and normally require specialized academic training for successful application. Models may be classified based on the characteristics they simulate and the way they handle temporal and spatial variations. Models of streamflow that predict the depth and velocity in a stream channel for a given geometry and discharge are most common, but models that include sediment movement, water quality, and some index of physical habitat quality are also widely used.

Stream ecosystem models simulate changes in habitat, biological populations, community structure, and ecological processes for stream ecosystems. Water quality (dissolved oxygen, temperature, suspended sediment, nitrogen and phosphorus) for streams and rivers are widely modeled for different regions and land use practices (Brown and Barnwell 1987; Lisle and Lewis 1992). Phytoplankton and benthic algae abundance along streams have been modeled for both streams and rivers (Brown and Barnwell 1987; McIntire 1973; McIntire et al. 1996; Stevenson and Smol 2002). Macroinvertebrate community structure and relationships to water quality and habitat have been modeled (Reynoldson et al. 1997; Karr et al. 1986; Hawkins et al. 2000). Hundreds of models are used around the world to relate the abundance of fish populations to physical habitat availability (Armour, Fisher, and Terrell 1984; Fausch, Hawkes, and Parsons 1988; Lee 1991). A recent review of models of large wood in streams identified 14 simulation models developed for streams and rivers (Gregory, Meleason, and Sobota 2003). In addition, several models simulate entire stream ecosystems (McIntire and Colby 1978; Newbold et al. 1983). Regional resource agencies often provide expertise to cooperating agencies and public groups to allow the application of more complex models in stream project design. A major limitation, particularly in models, is the poor linkage between ecology, water quality, and geomorphology. Multiple stressors are at work impairing health of many stream ecosystems, and it is often difficult to establish which are the most important.

A parametric model has parameters that must be estimated in some fashion. An empirical model contains any empirical relationship, one that is based on data. An empirical model is based, at least in part, on observed data, rather than a thorough understanding of the underlying physical principles. A lumped model describes processes on a scale larger than a point, while a distributed model describes all processes at a point then integrates processes over space and time to produce a total system response (Haan, Barfield, and Hayes 1994). A stochastic model is one whose outputs are predictable only in a statistical sense. Repeated use of a given set of model inputs produces outputs that are not the same, but follow certain statistical patterns (Haan 1986).

Model quality and capability vary widely. Several fundamental types of mathematical models are:

- Steady-state models predict conditions that occur for a given set of boundary conditions. For example, a flow model might predict the water surface elevation, given a fixed channel geometry and a constant flow.
- Unsteady models predict variations that occur with time such as during the passage of a storm hydrograph by dividing such an event into a series of steady-state time steps. Complex unsteady models have feedback loops that allow channel boundaries or other key variables to respond to inputs and change between time steps.

From a spatial perspective, models may be one-, two-, or three-dimensional:

- One-dimensional models only consider forces that occur in one (usually the streamwise) direction. Velocity and other stream properties may vary upstream and downstream, but not from bank to bank and not from the bed to the water surface. A common example is HEC–RAS.
- Two-dimensional models are usually depth averaged. They simulate variation in the horizontal plane, but assume no variation in the vertical.
- Three-dimensional models simulate variation in all three directions. Model cost, size, and complexity increase by roughly an order of magnitude with each added dimension.

## 654.0106 Key processes affecting stream corridor ecosystems

Stream channels are dynamic. Therefore, stream project planners and designers must be able to identify and understand key processes. Physical processes include hydrologic and geomorphic processes. Both biological and physical processes occur longitudinally, laterally (across the corridor), and vertically (above and underneath the corridor) over time. Abrupt changes in stream channels and their riparian areas by natural features (geologic differences along the river, vegetative changes related to geology, soils, or regional climate) and human activity (land conversion, urbanization, agriculture, forestry) often disrupt ecological processes.

### (a) Physical processes

**Longitudinal adjustment**

The longitudinal profile of a stream typically displays the effect of headwater erosion and downstream deposition over long periods of time. In the shorter timeframe, bed profiles may become locally steeper or more gradual, or they may exhibit aggradation (deposition of sediments) or degradation (channel deepening), as supplies of sediment and stream power fluctuate in response to changes in discharge. Since the energy gradient that drives the fluvial system is normally equal to the bed slope, other channel variables are quite sensitive to slope changes. Ecological impacts of slope change are generally related to changes in water velocity or sediment transport. For example, degradation of stream channels can lead to a lowering of the water table and consequent dessication and loss of riparian vegetation. Severe aggradation of stream channels decreases water depth and flow and can result in excessive temperatures or decreased dissolved oxygen during summer. Aggradation can also cause a lack of cover and smothering of coarse-grained substrates. During periods of low flow, aggraded stream channels may be too shallow to allow movement of fish. Excess sediment is most damaging where aquatic life is not adapted to these conditions.

### Lateral adjustment and bank erosion

Mean bank erosion rates vary from a few millimeters per year to 800 meters per year (Lawler 1993). Bank erosion is the result of about 10 processes, several of which are usually operating on a given site. Processes may be loosely grouped into hydraulic processes (removal of sediment by flowing water) or geotechnical processes (collapse, slumping, or sliding of sections of bank due to gravitational forces exceeding resisting forces). Hydraulic processes include scour of particles or aggregates of bank material. Fluid shear forces tend to be greatest for the bank toe, but erosion can occur anywhere on the bank, especially if not well vegetated. When the bank toe is eroded, often the upper bank is undermined, cantilever-type geometries result, and banks ultimately fall into the channel. Hydraulic processes also include erosion of the bank face by overbank flows that concentrate into rills and gullies, sometimes called valley trenches.

Geotechnical failures usually occur when large blocks of bank material fall into the channel from high, steep banks. These failures are often observed when erosion has lowered the channel bed, increasing bank height and angle. Shallow ground water flow toward the channel often facilitates failure by increasing soil weight, decreasing soil strength, creating voids by piping erosion, and lubricating planes of weakness. Geotechnical failure requires that banks be high and steep enough to create gravitational forces that exceed soil strength, which varies with soil type, soil moisture, vegetation, and other site-specific factors. A high bank may be only a few feet for noncohesive soils and more than 20 feet for cohesive soils.

Ideally, threshold channels (those for which hydraulic forces are at or below the threshold needed to initiate motion of boundary sediments) resist hydraulic erosion processes. Since alluvial channels are constantly shaped by streamflow, their banks are more mobile than threshold channel banks. However, rates of bank retreat vary widely from point to point along the bank and through time. For example, as an alluvial channel meanders freely across the flood plain, the current direction may shift, forcing the flow onto a section of bank that has been stable for years. A period of rapid bank erosion ensues. All channels experience some degree of bank erosion. Most sediment inputs are relatively small and are incorporated into stream corridor processes, such as flood plain development. Human activities can accelerate or decelerate bank erosion rates by orders of magnitude. In both cases, ecological impacts may be significant. Increased bank erosion can lead to deposition of clay and silts that is especially damaging to fish spawning habitats and habitats of benthic macroinvertebrates that live in the interstitial spaces of cobble and gravel substrates.

### Channel avulsion and flood plain construction

When bank erosion and longitudinal adjustment occur at a large scale, rapid changes in channel planform (avulsions or cutoffs) occur. These events typically occur during floods or high flows and trigger an episode of rapid local change in the region surrounding the avulsion. Typically, such events produce shorter, steeper channels in the short term, with erosion of upstream reaches and deposition in former channels and downstream. Channelization of streams often proceeds by construction of a series of artificial cutoffs to straighten the channel, with extreme impacts on channel stability if control structures or erosion resistant lining are not provided.

The impact of natural cutoffs is less than that of channelization because natural cutoffs normally occur one at a time, so that the overall length (and average bed slope) of a long reach does not change much. Since avulsions often trigger periods of large-scale, unpredictable instability, erosion control structures are often designed and placed to prevent them. However, in unmanaged stream corridors, major avulsions provide habitat complexity and diversity for aquatic species. Sloughs and oxbows that are abandoned channels provide low-energy habitats and refugia from the sporadic or seasonal fast water in the main channels. Newly deposited sediments in these areas and on the outside of meander bends provide substrate for pioneering plant species, while erosion topples older riparian forest communities and induces recruitment of wood to the stream. Flood plains that are periodically reworked by avulsions tend to be rich mosaics of plant communities of several successional stages. Over long periods of time, an unmanaged stream corridor will migrate back and forth across the entire valley, generally increasing the elevation of the flood plain through depositional processes. This generalization has exceptions such as deeply incised headwater streams or streams experiencing a drop in base level.

### Sediment transport

Sediments are transported and sorted during high flows, so flow regimes are critically important to aquatic species. Unaltered streams receive sediments from their watersheds, beds, and banks and subsequently sort these sediments by size into well-defined spatial patterns. Coarse sediments (larger gravel and cobble) occur along the axis of highest velocity and greatest depth, and finer sediments are deposited along the margins of stream channels or in the velocity shadow of larger inchannel obstructions (logjams, large boulders). Channel beds often feature a surface layer of coarse particles (armor) that is only one- or two-grain diameters thick, with a more heterogeneous mixture of sediment sizes underneath. Bed sediment size distribution or sediment texture is one of the most dynamic aspects of a fluvial system, changing rapidly in response to changes in other variables (channel bed slope, discharge, or amount of large wood). In turn, sediment transport is very sensitive to bed sediment size. Benthic organisms such as insects and small plants (periphyton) that live on the surface of coarse sediments are sensitive to changes in sediment size, sediment porosity, and the frequency of bed sediment movement. Biota from regions with naturally occurring fine-grained substrates are less sensitive to sediment than biota from regions with coarser-grained substrates. Fish that reproduce by laying eggs in gravel are particularly sensitive to changes in particle size, as they must rearrange stones to create redds. Also, well-aerated, intragravel flow is important for egg survival and larval growth.

Sediment sorting processes are less evident in fine sediment, where deposited in flood plain depressions, sloughs, and oxbows and within eddies along channel margins. These silty and clayey deposits provide media for colonization by terrestrial macrophytes when they are exposed by falling stages, or if they are low enough to remain under water, provide substrate for burrowing types of macroinvertebrates not found in the sandy main channel bed.

## (b) Ecological processes

### Energy flow and nutrient cycling

The flow of energy and nutrient dynamics in aquatic ecosystems occur in all dimensions and is influenced greatly by the physical dimensions of the stream channel. In turn, these processes strongly influence the community structure of stream ecosystems and the ecological processes along their longitudinal network. In small headwater streams, channels are narrow and shallow. In forested landscapes, inputs of solar radiation to the channel are, therefore, generally very small, and inputs of organic matter from the terrestrial ecosystem are relatively large.

Aquatic invertebrate communities are dominated by organisms that shred the larger terrestrial inputs (leaves, twigs) or by collectors that feed on the fine particles transported in from the terrestrial ecosystem or created by the shredding of large particles into smaller particles in the stream ecosystem. Since streams get larger as they flow downstream, channels generally become wider and deeper. Openings in the riparian canopy over the stream increase the inputs of solar radiation, causing increased production of algae and vascular aquatic plants, reducing the relative inputs of terrestrially derived organic matter. As a result, aquatic invertebrates are dominated by organisms that scrape algae off the streambed and collectors that feed on small particles of organic matter. The change in the longitudinal gradient of streams is also the primary factor driving hyporheic exchange flows (Harvey and Bencala 1993). This change creates unique physical, chemical, and hydrologic environments in streams and riparian zones, providing a diversity of habitats for many specially adapted macroinvertebrates (Stanford and Ward 2001).

The lateral exchange of water between a river and its flood plain is the driving force for nutrient cycling and the dynamics of the flood plain biotic community. Primary productivity of flood plain habitats is closely tied to hydroperiod, the periodic or regular occurrence of flooding or saturated soil conditions (Marble 1992), or the ratio of flood duration divided by flood frequency over a given period of time (Mitsch and Gosselink 1986). Productivity is greatest in wetlands with pulsed flooding (periodic inundation and drying) and high nutrient input, and lower in drained or permanently flooded conditions and low-nutrient water. Riparian wetlands may also influence stream channel morphology and flows, buffering the stream channel against the physical effects of high flows by dissipating energy as waters spread out onto the flood plain. Alternately, as streamflows recede, riparian wetlands provide water storage, slowly releasing water back to the stream through subsurface transport, thereby influencing stream baseflows.

### Recruitment of large wood

Wood is important from headwater streams to large rivers and estuaries (Maser and Sedell 1994). Wood

in the stream provides structure and organic matter that creates and enhances habitat diversity, and is a food source for many riparian and aquatic organisms (Boyer, Berg, and Gregory 2003).
Wood in streams also increases channel roughness and habitat complexity, triggers the formation of islands, and forms dams that trap leaves, twigs, and fine sediments. Fine particulate organic matter (particles smaller than 1 mm in diameter) retained by large wood pieces provides food for insects and other aquatic invertebrates.

Small, steep headwater streams with wood input often contain a series of step pools formed by fallen logs that cross the channel and trap smaller pieces of woody material and leaves. At the other end of the spectrum, some large rivers have been completely blocked by natural accumulations or rafts of large wood that dominate stream corridor processes (Triska 1984; Collins, Montgomery, and Sheikh 2002). Natural channel widening and bar formation associated with wood obstructions allow development of the short, braided reaches and secondary channels that are important spawning grounds for salmon and trout in the rivers of the Pacific Northwest. In the sand-bed coastal plain rivers of the southeastern United States, wood also provides important habitat for invertebrates and provides fish with a source of food (Wallace and Benke 1984). Therefore, in many streams and rivers throughout the world, fish abundance and diversity depend on accumulations of large wood.

Wood recruitment processes are complex since they involve site-specific variables (size, species, density, and condition of riparian trees, bank geometry, and erosion) and stochastic events (tree death, tree blowdown, high flows, bank failures). Continuously submerged wood resists decay for centuries, but wood subject to alternate wetting and drying may disintegrate and decay in less than a decade, with exact rates dependent on species and regional climatic factors (NEH654.14 and NEH654 TS14J). Transport of fallen wood is inversely related to the ratio of wood length to channel width; logs with lengths greater than channel width may lodge in place for a lengthy time period.

Removal of wood is perhaps the most widely practiced type of stream channel management, and the practice of removal (de-snagging or clearing and snagging) along with deforestation and removal of beaver have left many streams with only a trace of the large wood that existed previously. For a full description of the effects of wood in streams and rivers, see Gregory, Boyer, and Gurnell (2003).

## 654.0107 Stream corridor habitats

Stream channels are usually the focus of stream restorations, but how these channels are ecologically linked with other parts of the landscape, watershed, and corridor should be considered and addressed. The dynamic nature of streams and their response to floods and other disturbances create many diverse habitat types and conditions, both in the stream and along its corridor. These habitats and the processes that occur among them affect each other dramatically, adding to the habitat complexity and species interactions in the stream and riparian area. Stream corridors support a disproportionately rich biological community, relative to the rest of the landscape.

Confounding this ecologically valuable richness, however, are the challenges that river and stream processes such as flooding present to humans. Add to these the many human demands on streams as water supplies, and as agricultural, recreational, and urban development sites, and managers feel compelled to take actions that compromise the ability of watersheds to sustain important ecological functions of habitats. Stream corridors provide filtering, buffering, retention, and conduit functions for water, sediment, wood, chemical compounds, seeds, and habitat for aquatic and riparian organisms. Therefore, maintaining multidimensional connectivity along a stream corridor is important to maintaining the species and habitats within them.

### (a) Stream channel habitats

Instream habitats are as diverse as the systems that form them. High quality stream habitats are a mosaic of great spatial diversity created by various combinations of water quality and quantity, water depth, velocity, large wood substrates, mineral substrates, riparian vegetation, and the organisms that inhabit stream corridors. For example, shallow, swift flow over coarse bed material occurs in riffles that are often found at the inflection points of meanders. These habitats are important for stream invertebrates and as spawning sites. Generally speaking, aquatic organisms need what most organisms need to survive: clean water, oxygen, a steady food source, a place to hide or find refuge, and a place to successfully reproduce and grow to adulthood. Some aquatic organisms such as microscopic zooplankton live almost entirely in the water column; others, such as fish, use the water column and bottom substrates. Still others rely on the interstitial spaces of hyporheic habitats in and below the streambed.

Considerable research over the last several decades has described the importance of hyporheic zones to many alluvial stream corridor systems. These functions include:

- regulation of stream temperature by ground water upwelling
- water retention and storage which can reduce peak flows during floods and sustain baseflows during dry periods
- habitat creation, especially for aquatic invertebrates such as crustaceans, and vertebrates such as larval fishes
- buffering and filtering nutrients from streamflows and ground water
- aquifer recharge
- nutrient enrichment

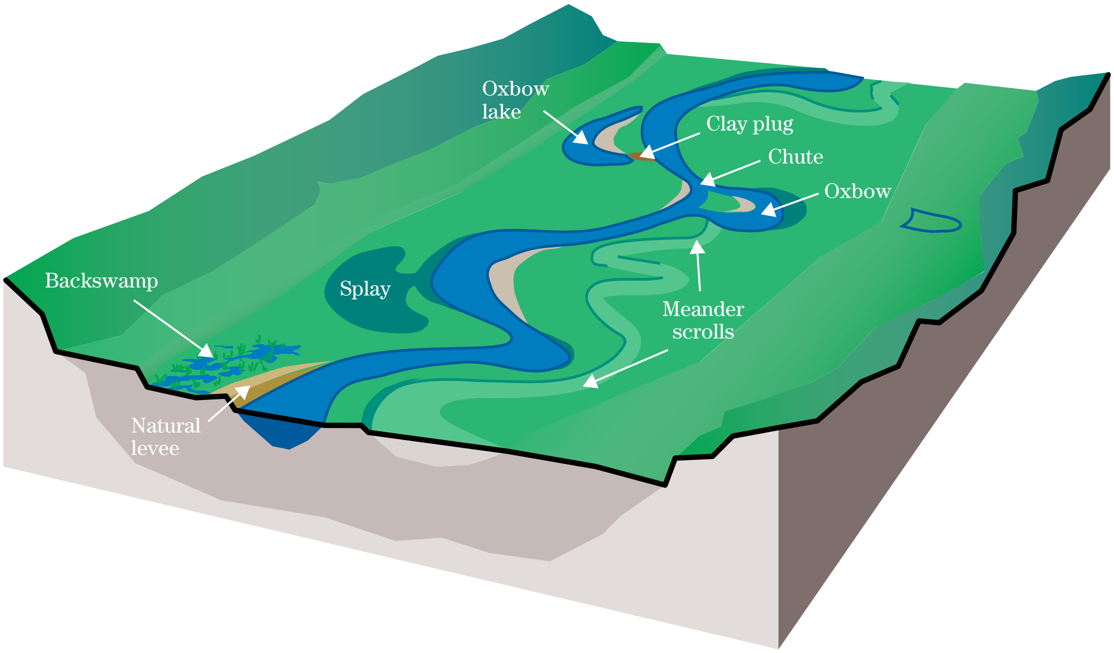
Most species use a variety of habitats during the course of their lives, some moving upstream or downstream, others into and out of the flood plain, a few into or out of the substrate, and still others to and from the ocean, all depending on the season, their age and physiology, and the conditions they face in their habitats. The complexity of their life cycles requires comparable complexity in their habitats and connections among them to allow movement at the appropriate time. To sustain aquatic communities, stream corridor project designers should consider the habitat needs of aquatic organisms throughout their life stages and the physical and ecological processes that provide them.

### (b) Riparian and flood plain habitats

A stream corridor is comprised of the stream channel and its riparian zone. The riparian zone forms an ecotone or transitional zone between the stream and uplands and provides value, both in productivity and biotic diversity, far greater than its relatively small area would indicate. Riparian zones may or may not include flood plains, depending on the valley form of the stream corridor. In relatively wide stream corridors, flood plains are prominent components of the riparian zone. Whereas stream channels have often been the focus of stream restoration projects over the past few decades, project designers today recognize the links between the stream channel and its riparian areas and flood plain or riparian wetlands. Projects that consider these linkages are becoming more common (Middleton 2002). Flood plain/riparian wetlands, which include swamps, oxbows, sloughs, ponds, backwaters, abandoned channels, and flood plain lakes, usually are remnants of historic river channels or shallower depressions created by scouring and sediment delivery associated with flooding (fig. 1–6). Riparian wetlands receive water from the stream during overbank flow events; however, runoff from adjacent uplands, ground water seepage, and precipitation can be significant or dominant contributors to wetlands depending on regional climate, soils, and other variables. During overbank flows, these wetland habitats are connected to the river by surface water, but as a stream recedes, water is trapped in low lying areas forming seasonal, isolated wetlands varying in size, shape, permanence, and significance for aquatic species.

The occurrence and relative importance of riparian wetlands in a stream ecosystem changes with stream gradient. High gradient streams are steep with small riparian zones, and few developed riparian wetlands. In contrast, lower gradient streams have broader riparian zones and flood plains characterized by more predictable hydroperiods and more extensive riparian wetlands systems. In these systems, flood plain wetlands can contribute significantly to stream ecosystem productivity and function.

**Figure 1–6** Flood plain features important for aquatic species



The hydrological characteristics of wetlands vary from permanently flooded backwaters to wetlands that have overland sheet flow during floods, to ephemeral, isolated pools. In lower gradient streams, plants, invertebrates, and vertebrates have evolved survival strategies that depend on occasional or seasonal flooding or ponding. Some macroinvertebrates complete their entire life cycle in these habitats, persisting in seasonal wetlands in a drought resistant form, such as an egg. Vertebrates (fish, amphibians, mammals, and birds) frequently make seasonal movements into flood plain wetlands (from the stream, wetlands outside the flood plain, or surrounding uplands) and time key periods of their life cycle (breeding, rearing young, or migration) to riparian zone ponding and flooding. Riparian wetlands are also important habitats in stream corridors as they provide low velocity refugia for organisms that benefit from stream processes, but cannot survive for long periods in moving water, such as frogs. Temporary and seasonal flood plain wetlands provide vernal pool habitat for amphibians and other organisms. Importantly, simply returning water to a stream's flood plain is not adequate for reestablishing function for all organisms, because each may be dependent on a specific timing, depth, duration, or frequency of flooding.

Just as riparian wetlands can influence stream function, anthropogenic changes in stream channel morphometry can influence the function of a flood plain wetland. Riparian wetlands are often filled or isolated from the stream by constructed levees, channel incision, or channel straightening projects. Physical isolation changes the hydroperiod and precludes access to the flood plain by many stream obligate organisms (fish). Channelization can result in streambed incision that changes the frequency of overbank flows, and therefore, the hydroperiod of flood plain wetlands. In urban areas, stream incision causes loss of riparian wetlands by lowering the flood plain water table. Similarly, channel stabilization usually precludes avulsive processes (a sudden change of course of a stream) that can form new flood plain wetlands and create complex mosaics of different successional stages. This latter point is critical to maintaining habitat diversity in the riparian zone. Therefore, stream restoration projects that produce normal overbank flooding regimes can be more successful at restoring stream ecosystem function and the species that depend on them.

## 654.0108 Disturbance and response in aquatic ecosystems

### (a) Definitions of disturbance

Fluvial systems can experience abrupt changes in environmental conditions that are often considered to be disturbances. However, simple variation in physical (discharge, sediments) or environmental (temperature, dissolved oxygen) conditions are inherent in any system and should not be considered disturbances without the context of their effects on ecosystems. The most widely accepted definition of ecological disturbance is: "*… any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, and the physical environment*" (White and Pickett 1985). Fluvial ecosystems are inherently variable and can be naturally subject to wide ranges in flow conditions.

Stream ecologists have limited this general ecological definition of disturbance to include only those events characterized by frequency and intensity that are outside a predictable range (Resh et al. 1988). These definitions separate disturbances from inherent variation in terms of (1) the disruption of a biological system, (2) the change in resources or physical environment, and (3) rarity or unpredictability outside a range of commonly observed variation. It is important to recognize that disturbances are not just events that cause decreases in abundance of organisms. In these definitions, any event that disrupts—either increasing or decreasing—the structure of the ecosystem, community, or populations of species is considered a disturbance. For example, abrupt releases of fertilizers that cause an increase in algae would be considered a disturbance.

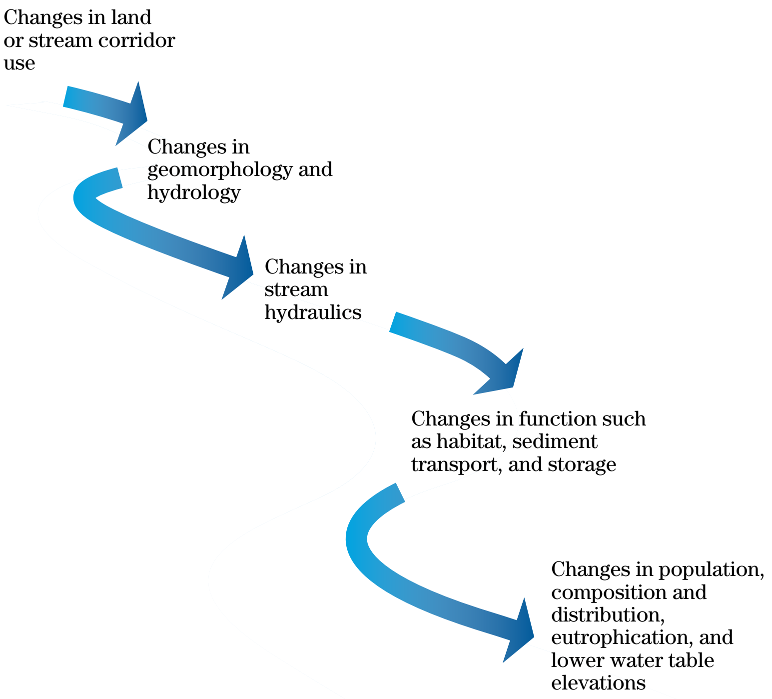
The biological communities and physical form of a stream, river, riparian corridor, or watershed exhibit the influences of small- and large-scale disturbances that have occurred (fig. 1–7 (FISRWG 1998)). Natural disturbances include floods, fire, drought, or storms. Disturbances induced by land management actions are more aptly called perturbations and include such activities as timber harvest, urban development, dam construction, and agricultural production. The intensity, magnitude, duration, recurrence intervals, and interactions of a disturbance or perturbation affect the manner in which fluvial systems respond to them.

## (b) Physical responses to disturbances

The U.S. Army Corps of Engineers (USACE) (USACE 1994d; FISRWG 1998) describe disturbances in rivers and the physical responses of channel form and bed composition. Over some timeframe, stream systems tend to seek a condition of equilibrium. However, the behavior of fluvial systems is nonlinear due to time lags in response and the existence of thresholds (Schumm 1977). An illustration of a threshold in a fluvial system is the response of a hypothetical channel to urbanization. Initial deforestation and construction within the watershed produces little change in channel morphology, but when the impervious area of the watershed exceeds a threshold, for example 10 percent, rapid bed and bank erosion occur.

These types of nonlinear behavior often result in a complex response (Schumm 1977), defined as a response to disturbance that is *not* progressive and systematic. Another example of a complex response is provided by the changes in bed elevation that occur downstream from a hydraulic control structure such as a culvert, bridge crossing, weir, or dam. A dam placed on a hypothetical stream reduces sediment supply downstream, leading to bed scour and degradation. In addition, the lower flood stages affect base levels for tributaries, triggering incision and headward progressing bed erosion within the tributary watersheds, contributing sediments to the main channel below the dam. However, since flood flows are reduced by operation of the dam, the main channel is no longer capable of moving larger size particles, leading to long-term main channel bed aggradation. For many small watershed projects, changes in land cover and channelization have triggered instabilities that resulted in incision of upstream tributaries and aggradation along the main stem. The main stem aggradation reduces

**Figure 1–7** Disturbance to a stream corridor system typically results in a causal chain of alterations to stream corridor structure and function.



channel capacity and increases the frequency of flooding. Small dams can stop the migration of headcuts and reduce flood peaks along the main stem.

Often macroscale stream corridor features are created or destroyed by the influence of large scale disturbances such as glaciation, earthquakes, tectonic movements, volcanic eruptions, large forest fires, and climate change. These processes and events affect watersheds on a regional or even continental scale. At a smaller scale, floods can alter a stream corridor. Disturbances can gradually or suddenly transform the bed type, planform, or cross section of a stream reach and its flood plain and riparian area. Stream project planners and designers usually have no way to influence natural disturbances or upstream human perturbations on the landscape, but they should be aware of their impact on the stream system of interest. Inadequate consideration of disturbances can rapidly diminish the sustainability and benefits of stream restoration and protection projects. The responses of aquatic species to disturbances depend on the scale of the disturbance, the population structure of the species, and the connectivity of the watershed both before and after the disturbance.

Streambeds within the active stream channel experience the greatest frequency of geomorphic disturbance that may be on the order of every year or two (sediment transporting events). Side channel and backwater areas are not as frequently disturbed, but are affected by higher flow events and channel avulsions (perhaps 5- to 10-year flows). Generally, flood plains have even less frequent disturbances than the main and side channel; it may require a 10-year or larger flood event before a flood plain can be significantly altered. Terraces and hill slopes typically have the lowest frequency disturbance regime when placed in context of stream processes (slope failures and mass movements). Common to all of these disturbances is the episode of disturbance followed by a period of recovery. If the disturbances become so frequent that the system cannot recover before the next disturbance event, then the stream is held in a constant state of disequilibrium or instability (National Oceanic and Atmospheric Association National Marine Fisheries Service (NOAA Fisheries Service) et al. 2006). In these situations, the concept of dominant discharge (channel-forming discharge) is not applicable.

### Change in discharge

Long-term changes in discharge magnitude or duration have important implications for channel form and process. Urbanization, deforestation, and fires destroy vegetative cover, increase peak discharges, and lead to channel erosion, while flood control impoundments dampen peak discharges, and smaller, simpler channel forms develop downstream. Sharp increases in peak discharge and resulting decreases in baseflow are often observed in smaller watersheds undergoing development. Conversely, urban stormwater management activities may significantly increase the time that the flow is at bankfull stage, causing an increase in channel erosion. Changes in the discharge may also produce changes in water quality, sediment yield, bed sediment texture, pool habitat availability, and flood plain ecosystems that depend on lateral channel migration processes. Impacts for certain threshold-type channels may be particularly severe if flow forces required for bed movement occur much more frequently under the new discharge regime.

### Changing sediment loads

Watershed developments and agricultural practices often generate higher sediment loads. Sediment can be a major concern for water supply reservoirs and navigation channels. Elevated sediment loads may cause real or perceived detrimental impacts on the stream and receiving water ecosystems. Impacts tend to be most severe in coarse-bed threshold systems with low turbidity and normally stable bed conditions. Elevated loads of sand and finer material may blanket gravel or cobble riffles, filling interstitial spaces that are key habitats for invertebrates and gravel-spawning fish. Elevated sediment loads in alluvial systems can result in filled or plugged channels that overflow many times a year and provide little deep water habitat. In other cases, elevated sediment loads have triggered accelerated channel widening or even a shift in channel form from single-thread to braided, with consequent changes in the riparian and aquatic community structure.

### Changing water and sediment discharge

When both water and sediment discharge regimes change, fluvial response may be more complex. In the absence of complicating factors, a decrease in bed-material load and water discharge might produce a narrower or shallower channel. If bed-material and water discharge both increase, but water discharge increases more, the alluvial channel will become wider and deeper. For example, in long-term urbanization, the frequency and magnitude of discharges increase, triggering channel erosion. If sediment supply and water discharge both increase but sediment supply increases more, channels will become wider and shallower.

**Changing bed sediment size**

Any of the mentioned changes can cause shifts in bed sediment size. Bed sediment size and frequency of movement is a fundamental characteristic of stream habitats that is used to classify or organize stream habitats at the reach scale (Shields and Milhous 1992). However, bed sediment size can change rapidly in disturbed watersheds, in response to changing hydraulic conditions and changes in sediment supply (Doyle and Shields 2000). Formation and destruction of armor layers (layers of coarse sediments on the surface of more heterogeneous deposits) may control the frequency of bed movement and stability. Feedback loops occur in fluvial systems since bedforms, flow resistance, depth, and velocity are governed by bed sediment size.

**Changing channel geometry**

Erosion that produces channel widening or deepening over a long reach usually signals a change in inputs (increasing discharge) or boundary conditions (lowering a water table leading to death of riparian vegetation and accelerated bank erosion). Changes in channel geometry are also symptomatic of systemic erosion and deposition that accompany channel incision. The most direct result of changes in channel cross-sectional areas is shifts in water depth and velocity at flows that do not overflow the channel banks and the loss of flood plain wetlands and other habitats.

These changes have major implications for aquatic organisms. As larger channels convey higher flows without overflow, more of the erosional forces are focused on the channel bed and banks, rather than dissipated across the flood plain. This can result in loss of productive lands adjacent to the river, loss of riparian vegetation, and discontinuity of stream corridor processes.

## (c) Responses of stream corridors to flooding

**Physical responses**

Unaltered streams usually overflow their banks regularly. Although current thinking among designers is that stream geometry (width, depth, slope) reflects a channel-forming discharge (Copeland et al. 2001), debate continues about the relative influence of rare, extremely large floods. Regional factors such as relief, geology, vegetation, and weather patterns govern the geomorphic significance of large floods relative to smaller ones (Werrity 1997). Clearly, major changes in channels and flood plains occur during high flows. Perhaps less obvious are important ecological functions that occur due to exchanges of water, sediment, nutrients, and organisms between the main channel and the flood plain during floods. The fact that flood plains along large rivers owe their fertility to seasonal floods that deposit thin layers of silt has been recognized for millennia, but the key role that low-velocity regions on flood plains play as refugia and nurseries for aquatic organisms has not. Flooding and associated erosion are often managed or eliminated by water resources projects due to their perceived and real deleterious effects on riparian land uses such as crop production and recreation.

**Ecological effects of floods on stream ecosystems**

Floods are the most common type of natural disturbance in streams (Resh et al. 1988; Fisher 1990). These high-flow events erode, transport and deposit sediments on flood plains, move large wood, add trees into the channel, flush fine sediments and silts out of streambeds, and transport nutrients and organic matter into streams from the surrounding terrestrial ecosystems (Junk, Bayley, and Sparks 1989; Gregory et al. 1991). The effects of disturbances on stream ecosystems have been reviewed extensively (Ward and Stanford 1983; Niemi et al. 1990; Steinman and McIntire 1990; Wallace 1990; Yount and Niemi 1990; Lake 2000). Aquatic organisms have evolved to not only withstand the potential impacts of floods, but actually benefit from these events (Kimmerer and Allen 1982; Meffe 1984; Matthews 1986; Remillard, Gruendling, and Bogucki 1987; Bayley 1991; Allan and Flecker 1993). For example, trout and salmon deposit their eggs in gravel nests or redds. Silt and fine sediments can smother the eggs and prevent emerging alevins from reaching the stream surface. Floods flush the fine sediments from gravel deposits in streams and create a variety of areas for spawning and clean gravel environments and habitats for rearing fry and juvenile trout and salmon. However, the ecology of trout and salmon is synchronized with these seasonal high flows or floods, so that sensitive life stages (eggs and alevin) are usually absent or physiologically capable of surviving channel flushing events.

Aquatic organisms differ greatly in their life histories, their vulnerability, and their ability to recover from disturbances (Resh et al. 1988; Yount and Niemi 1990; Lake 2000). The recovery of stream and river ecosystems following disturbances was the focus of a special issue of Environmental Management in 1990. A review of field studies of responses to flooding reveal that, in general, algae and microbes recover in days to weeks, macroinvertebrates recover in less than a year, and fish recover in 1 to 2 years, with a few species requiring decades (Yount and Niemi 1990). The conditions of the ecosystem and riparian corridors are critical factors in determining resistance to the disturbance and the subsequent rate of recovery (Reeves et al. 1995). Refugia from disturbances are important factors in recovery and the design of stream restoration projects (Sedell et al. 1990). Flood plain rivers are larger and more complex than small streams, but the enormous power and frequency of flooding create natural processes for restoring large rivers and their flood plains (Bayley 1991; Sparks et al. 1990).

**Disturbances as restoration processes**
Disturbance processes, such as floods, fire, and droughts are natural processes of restoration (Gregory et al. 1991; Sedell et al. 1990; Sparks et al. 1990; Reeves et al. 1995). Design of restoration projects or changes in stream management should consider the frequency and location of disturbance events and make certain that their beneficial effects of floods and other disturbances are not negated by the rush to harden streambanks, prevent channel change, and remove habitat features that provide complexity and heterogeneity (large wood, gravel bars, islands, sloughs). In some areas, past projects that were originally designed to minimize the effects of disturbances (levees, riprap, tidal gates) are being removed to restore streams, rivers, and estuaries (CALFED 2003). Restoration projects also should consider natural processes of riparian regeneration (Boyer, Berg, and Gregory 2003). River channels may reoccupy old or abandoned side channels, if revetments and other barriers are removed. Careful design and analysis can achieve a balance between taking advantage of the restorative processes of natural disturbances and the need to protect property and communities from them.

## 654.0109 Human land uses and their effects on stream corridors

The ecological integrity of stream corridors is intrinsically related to the pattern of streamflow (Poff et al. 1997). The magnitude and timing of water and sediment inputs reflect watershed land use. Their effects on physical habitat and biological communities follow (Wang et al. 1997). Refer to table 1–2 for a list of physical responses of stream corridors to human activities (Gregory and Walling 1973).

### (a) Agricultural land use

Typically, both water and sediment runoff increase, and infiltration decreases when forests or grasslands are cultivated or grazed. Irrigation return flows to streams can diminish water quality, but generally do not increase sedimentation and erosion to the extent cultivation and grazing do. Impacts of livestock grazing on stream corridors include destruction of riparian vegetation, soil compaction, bank erosion, water pollution, and degradation of fish habitat and riparian habitat quality. Destruction of vegetation by livestock or by farm equipment may be more damaging adjacent to channels with relatively erosion-resistant beds; if banks are more erodible than the bed, flow energy directed against the banks may produce channel widening and loss of productive land. However, the severity of impacts diminishes when grazing management practices are designed to accommodate seasonal conditions, watershed soils, slopes, climate, and other factors. Similarly, effects of cultivation on stream corridors can be mediated by using conservation practices such as conservation tillage, grassed waterways, and riparian buffers.

### (b) Woodland and timber management

Forest management activities affect stream corridors. Regional changes in precipitation runoff relationships have been attributed to development (afforestation or reforestation) or clearing of woodlands. Clearing is usually associated with reduced infiltration and increased runoff and sediment loading. Forestry practices also affect large wood recruitment to streams. Although forests often regenerate rapidly following

**Table 1–2** Types of human activities that produce physical changes in stream corridors

| Change in stream corridors | Human modifications | Form affected | | |
|---|---|---|---|---|
| **Direct changes** | | | | |
| Drainage changes | Irrigation networks | | N | |
| | Drainage schemes | | N | |
| | Agricultural drains | | N | |
| | Ditches | | N | |
| | Road drains | | N | |
| | Stormwater sewers | | N | |
| Channel changes | River regulation | G | P | |
| | Bank stabilization | G | P | |
| Water and sediment balance | Abstraction of water | G | | |
| | Return of water | G | | |
| | Waste disposal | G | | |
| **Indirect changes** | | | | |
| Land use | Cropland | N | P | G |
| | Building construction | | P | G |
| | Urbanization | N | P | G |
| | Afforestation | N | P | G |
| | Reservoir construction | | P | G |
| Soil character | Drainage | | | |
| | Plowing | N | | |
| | Fertilizers | N | P | |

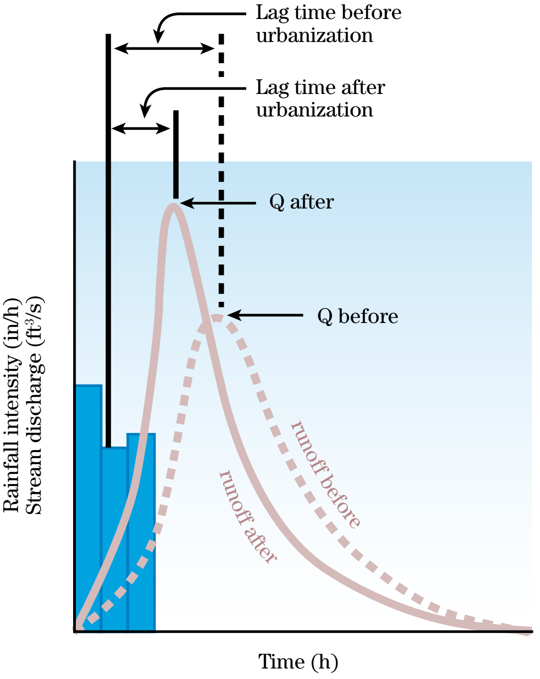
N=modifications of drainage network
G=channel geometry
P=channel planform

harvest (either due to natural succession or replanting), roads and stream crossings may have severe, long-term impacts on stream habitats if not properly designed and maintained. Best management practices such as riparian buffers of minimum widths mitigate the environmental effects of timber harvesting. There are local and regional variations in regulations, and therefore, variable success at protecting stream corridor resources.

## (c) Urban development

The primary effects of urbanization are increased surface runoff and reduced baseflows (fig. 1–8). High-flow events of a given magnitude become more frequent (Moscrip and Montgomery 1997). During initial development, sediment yield may increase by an order of magnitude or more, but usually declines as construction projects are completed (Wolman and Schick 1967).

**Figure 1–8** Typical effects of urbanization on flow event hydrograph



Over a longer term, urbanization increases the area of impervious surfaces (parking lots, roads, and roofs) which increase runoff and peak flows by eliminating undeveloped land where infiltration can occur. Impacts of urbanization on stream ecosystems occur due to shifts in hydrology that alter stream habitats, such as fine sediment deposition, depletion of large wood, destruction of riparian vegetation, and significant water quality degradation from point and nonpoint pollution (Moscrip and Montgomery 1997). Baseflow in urban streams may be comprised primarily of wastewater discharges and irrigation return flows. Even low levels of urbanization (8% to 12% connected impervious area) impair stream ecosystems (Wang et al. 2001; Wang and Lyons 2003). However, effects may be mitigated by interspersing vegetated plots with impervious zones and maintaining riparian buffers along streams. An extensive review of literature about the effects of urbanization on stream ecosystems is provided by Paul and Meyer (2001).

## (d) Mining activities

Mining activities have perhaps greater potential for damaging stream corridor resources than any other human endeavor (Macklin and Lewin 1997). Mines may be constructed above or below ground. Subsurface mines change hydrologic relationships, and in some cases, long reaches or entire streams may be diverted into abandoned underground mines. Drainage from subsurface mines often can be acidic and can contain elevated concentrations of heavy metals. Surface mines are sometimes constructed within channels or on flood plains immediately adjacent to channels, and changes in surface topography and channel volume are great enough to trigger large-scale channel instability or to transform lotic habitats into lentic habitats. Gravel removal from streams may result in changes in streambed type and morphology for long distances and times due to the diversion of coarse bed load from the stream corridor, complicating rehabilitation efforts (Brown 1998), and rendering spawning habitats unusable.

Many stream corridors continue to respond to disturbances created by hydraulic or dredge mining over a century ago. In other cases, watersheds have sustained drastic changes in topography, drainage networks, and vegetative cover due to extremely acidic or infertile soils that have been exposed by mining or disposal of mining wastes. Dispersal of heavy metals and radionuclides derived from mining or smelting is particularly detrimental (Macklin 1996).

## (e) Exotic or invasive plants and animals

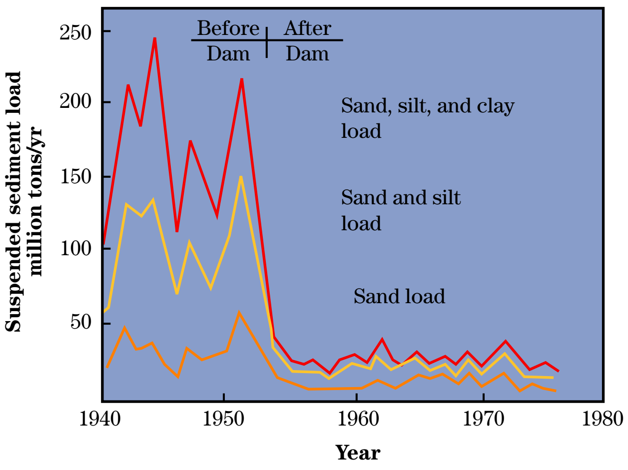
Exotic, or nonnative species, occur in many stream corridors, and management of these organisms is often a necessary component of rehabilitation or restoration projects. Invasive alien species are defined as nonnative organisms that cause, or have the potential to cause, harm to the environment, economy, or human health (Pimentel et al. 2000). Examples of invasive animals are zebra mussels and stocked game fish that supplant native species. These species compete with native species for niche resources, often leading to declining habitat quality and biodiversity. For example, the exotic vine, kudzu (*Pueraria lobata*), was imported from Asia in the nineteenth century and planted along stream corridors in the Southeast for erosion control. In recent decades, kudzu has hindered recovery of native riparian woody plants in stream corridors (Shields, Bowie, and Cooper 1995), and is viewed as a nuisance pest by forest managers. The exotic salt cedar (*Tamarix chinensis*) thrives in dammed rivers and stream corridors of the arid West and Midwest, excluding cottonwood, willow, and many other native riparian species (FISRWG 1998).

## (f) Dams and diversions

Dam construction has affected all of the watersheds larger than about 2,000 square kilometers within the continental United States (Graf 1999). Dams typically moderate peak flows and trap sediments (fig. 1–9 (adapted from USACE 1994d)), but additional perturbations also occur depending on the operating conditions and site-specific variables. Grant, Schmidt, and Lewis (2003) reviewed existing information regarding downstream physical effects of dams and proposed a conceptual model based on sediment supply and the change in the frequency of sediment-transporting flows produced by the dam. Dams typically increase water depth and decrease velocity upstream, transforming lotic habitats to lentic conditions. Dams reduce peak flows downstream, resulting in narrower channels with more uniform flood plain vegetation. In some cases, braided channels may be transformed to single-thread forms. Bed material becomes more stable and interstitial voids fill with fines since flows high enough to flush gravels are less frequent. Water quality impacts include major changes in water temperature, turbidity, and nutrient levels. Dams also are a barrier to migration for aquatic species, as well as the flow of energy and materials, leading to fragmentation of habitat and ecological processes critical for sustaining aquatic species (Poff and Hart 2002). Dams can also block coarse sediment transport which, in some cases, results in channel incision downstream. Dams also reduce the delivery of large wood to downstream reaches.

Removing dams is an increasingly common practice, particularly where the dam is no longer needed, costs of maintenance and repair do not warrant continued operation, or environmental values upon removal exceed those provided by the dam. Dam removal projects create technical and political challenges, and the environmental effects may be negative, as well as positive. Of particular concern is the management of sediments stored by the dam, as this sediment may contain contaminants from the watershed. A review of information related to dam removal is provided by the Aspen Institute (2002), and the base of knowledge in this area is rapidly expanding. Other references addressing aspects of dam removal include Schuman (1995); Doyle and Shields (2000); Bednarek (2001); Grant (2001); Pizzuto (2002); and Doyle, Stanley, and Harbor (2003).

**Figure 1–9** Effect of storage reservoir on downstream sediment transport (Missouri River average annual suspended sediment load at Omaha, NE)



By their very nature, water development projects such as dams and diversions alter the timing, duration, magnitude, and frequency of streamflow in a river system (Ward and Stanford 1979; Lillehammer, Brittain, and Saltveit 1984; Petts 1984; Gore and Petts 1989; Calow and Petts 1994; Church 1995; Ligon, Dietrich, and Trush 1995; Ward and Stanford 1995a, 1995b; and Stanford et al. 1996 for extensive treatments of this subject). Importantly, dams and diversions can substantially alter fisheries and riparian habitat along regulated stream reaches (Lane 1955a; Williams and Wolman 1984; Ligon, Dietrich, and Trush 1995; Montgomery and Buffington 1998; Buffington and Montgomery 1999; Shields, Knight, and Cooper 2000).

## (g) Channel modification projects

Channel modifications are frequently implemented for flood control, drainage, erosion control, or to relocate channels for construction of various types of infrastructure. Changes in channel geometry can trigger significant fluvial response and usually require erosion control structures like weirs or revetments. Many stream management projects address physical or ecological damages produced by channelization projects constructed between 1950 and 1970 (Brookes 1988; Bolton and Shellberg 2001).

The USACE (1994d) ranks changes in the channel cross section by their potential for creating channel stability problems (from lowest to highest) as shown in table 1–3.

Generally speaking, the more dynamic a channel reach is before alteration, the more likely that changes in channel cross section will cause stability problems (USACE 1994d) (tables 1–4 and 1–5).

## (h) Recreation

Stream corridors provide recreational opportunities such as swimming, boating, fishing, hiking, hunting, bird watching, and photography. The sensitivity of stream corridors to recreational use varies with soils, climate, topography, and intensity of use (FISRWG 1998). Intense foot or vehicle traffic may compact soils, destroy vegetation, and trigger flow concentration and erosion. Power boating can cause bank erosion due to wave wash, and accidental spills or waste discharges can degrade water quality. Fish and wildlife may be impacted by over harvesting or disturbance. Littering, noise, erosion, and vandalism degrade stream corridor aesthetics.

**Table 1–3** Stability rankings for various channel cross-sectional changes

| Stability Ranking (1 = low, 10 = high) | Stream cross-sectional change |
|---|---|
| 1 | Nonstructural flood control measures (flood-proofing structures, warning systems) |
| 2 | Levees set back clear of the meander belt |
| 3 | Levees within the meander belt |
| 4 | Off-channel detention basins |
| 5 | Upstream flood retention basins or reservoirs |
| 6 | Flood bypass channels |
| 7 | Clearing and snagging (removal of large woody debris or bank vegetation) |
| 8 | Enlarged cross section with the existing low-flow channel left intact |
| 9 | Channel widening |
| 10 | Channel deepening |

**Table 1–4** Typical features and stability problems associated with streams

| Channel type | Typical features | Stability problems |
|---|---|---|
| Mountain torrents | Steep slopes<br>Boulders<br>Drops and chutes | Bed scour and degradation<br>Potential for debris flows |
| Alluvial fans | Multiple channels<br>Coarse deposits | Sudden channel shifts<br>Deposition<br>Degradation |
| Braided rivers | Interlacing channels<br>Coarse sediments (usually)<br>High bed load | Frequent shifts of main channel<br>Scour and deposition |
| Arroyos | Infrequent flows<br>Wide flat channels<br>Flash floods<br>High sediment loads | Potential for rapid changes in platform, profile, and cross section |
| Meandering rivers | Alternating bends<br>Flat slopes<br>Wide flood plains | Bank erosion<br>Meander migration<br>Scour and deposition |
| Modified streams | Previously channelized<br>Altered base levels | Reduced activity<br>Degradation and aggradation<br>Bank erosion |
| Regulated rivers | Upstream reservoirs<br>Irrigation diversions | Reduced activity<br>Degradation below dams<br>Lowered base level for tributaries<br>Aggradation at tributary mouths |
| Deltas | Multiple channels<br>Fine deposits | Channel shifts<br>Deposition and extension |
| Underfit streams | Sinuous planform<br>Low slope | Meander migration |
| Cohesive channels | Irregular or unusual planform | Variable |

**Table 1–5** Rating of channel modifications for effects on channel stability

| Type of channel modification | Mountain torrent | Alluvial fan | Braided, multiple channel stream | Arroyo | Meandering stream | Modified stream | Regulated stream | Delta | Underfit stream | Cohesive stream |
|---|---|---|---|---|---|---|---|---|---|---|
| Nonstructural flood proofing, flood warning, evacuation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Levees set beyond stream meander belt | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 |
| Levees set within stream meander belt or along bankline | 2 | 5 | 5 | 4 | 3 | 3 | 2 | 4 | 2 | 2 |
| Off-channel flood detention basin | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 |
| Within-channel flood detention basin | 4 | 5 | 5 | 5 | 4 | 4 | 3 | 4 | 2 | 2 |
| Major flood storage reservoirs | 3 | 4 | 4 | 4 | 3 | 3 | 2 | 3 | 1 | 1 |
| Floodway, diversion, or bypass channels | 4 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 3 | 3 |
| Removal of bank vegetation or large wood (clearing and snagging) | 6 | 6 | 5 | 5 | 7 | 7 | 5 | 5 | 5 | 5 |
| Compound channel, low-flow pilot plus flooding berms | 5 | 8 | 8 | 7 | 7 | 6 | 6 | 7 | 4 | 4 |
| Significant channel widening | 6 | 9 | 9 | 8 | 8 | 6 | 7 | 7 | 5 | 5 |
| Significant channel widening and deepening | 7 | 9 | 9 | 9 | 9 | 9 | 8 | 8 | 8 | 7 |
| Significant channel widening, deepening, and straightening | 8 | 10 | 10 | 10 | 10 | 8 | 9 | 9 | 7 | 8 |

Note: Qualitative rating of 1 (low) to 10 (high impact on stability)

## 654.0110 Summary of ecological principles to guide stream designs

Fluvial systems are dynamic. They change over time and in space in response to their hydrology and geomorphology, and the interactions of these physical processes with biotic communities (bacteria, plants, animals). To protect species, habitats, and water resources, managers must incorporate environmental features into stream project designs (Shields et al. 2003). Historically, engineered solutions to stream channel problems featured constrained physical systems. Today, resource managers and stream design engineers are seeking ways to modify tried and true designs to allow minimally constrained natural ecological processes to be restored. The following principles of stream restoration design incorporate ecological considerations to facilitate such modifications:

- Base designs on ecological principles, as well as physical ones. To the extent possible, restore or maintain the inherent complexities of stream corridors, ecological linkages, and their physical connections. For example:
  - Incorporate native vegetation into design of flood control structures, revetments, levees, and other hard structures.
  - Incorporate silvicultural treatments to maximize generation of trees, specifically for large wood recruitment.
  - Incorporate livestock and/or recreational management regimes into stream design projects to protect restoration or conservation investments in riparian zones and sustain their functions.
  - Remove hard structures no longer deemed necessary or functional in the watershed due to changes in the physical and ecological conditions.
  - Work with partners such as USACE and the U.S. Bureau of Reclamation (USBR) to restore natural hydrologic regimes to the extent possible.
  - Protect life and property.
- During the design process, integrate the disciplines of fluvial geomorphology, geology, hydrology, aquatic and riparian ecology, sedimentation engineering, and hydraulic and geotechnical engineering. If possible, collect baseline and post-implementation data to validate successful designs of innovative approaches to stream corridor restoration. Publish and distribute the information so that it can be used by other designers in the future.
- Design for site-specific response in a watershed-scale context. Consider factors affecting stream corridor processes at different spatial scales, from landscape to watershed to microhabitat, as well as factors that influence the long-term population status and dynamics of aquatic species and the community of species with which they interact. Seek technical advice regarding aquatic species from local experts and state fish and wildlife agencies.
- Consider ecological costs and values, as well as project and long-term maintenance costs of engineered solutions to channel problems. Projects that are compatible with the inherent tendencies of stream corridor systems tend to be more stable, require less maintenance, and are more ecologically productive than traditional engineered approaches (Brookes 1989). These advantages should be emphasized when determining design options.