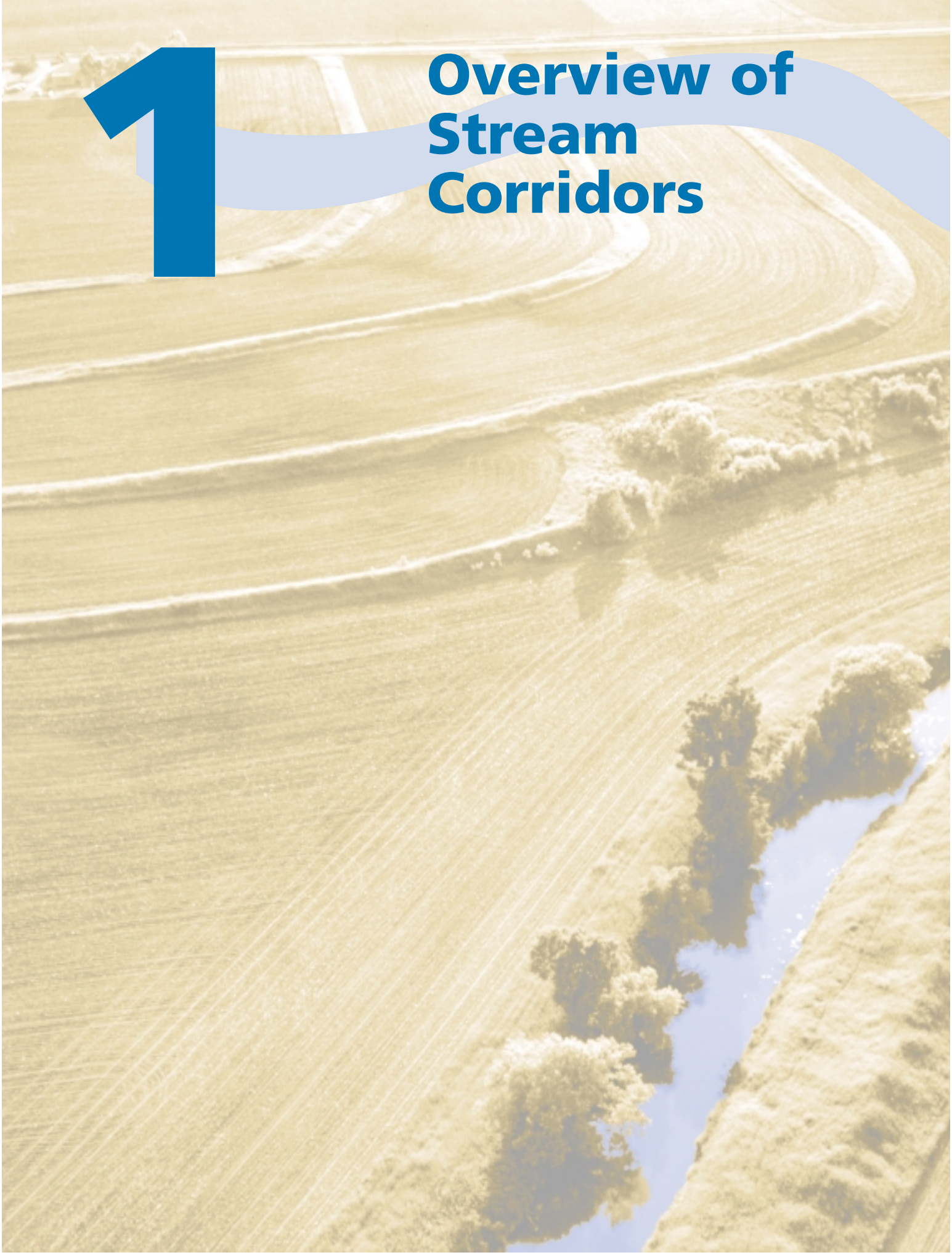
1 Overview of Stream Corridors



1.A Overview of Structure and Scale

- *What are the structural components of a stream corridor?*
- *Why are stream corridors of special significance, and why should they be the focus of restoration efforts?*
- *What is the relationship between stream corridors and other landscape units at broader and more local scales?*
- *What scales should be considered for a stream corridor restoration?*

1.B Stream Corridor Functions and Dynamic Equilibrium

- *How is a stream corridor structured from side to side?*
- *How do these elements contribute to stream corridor functions?*
- *What role do these elements play in the life of the stream?*
- *What do we need to know about the lateral elements of a stream corridor to adequately characterize a stream corridor for restoration?*
- *How are the lateral elements of a stream corridor used to define flow patterns of a stream?*

1.C A Longitudinal View Along the Stream Corridor

- *What are the longitudinal structural elements of a stream corridor?*
- *How are these elements used to characterize a stream corridor?*
- *What are some of the basic ecological concepts that can be applied to streams to understand their function and characteristics on a longitudinal scale?*
- *What do we need to know about the longitudinal elements that are important to stream corridor restoration?*

1 Overview of Stream Corridors

1.A Physical Structure and Time at Multiple Scales

1.B A Lateral View Across the Stream Corridor

1.C A Longitudinal View Along the Stream Corridor

A stream corridor is an ecosystem that usually consists of three major elements:

- *Stream channel*
- *Floodplain*
- *Transitional upland fringe*

Together they function as dynamic and valued crossroads in the landscape.

*(**Figure 1.1**). Water and other materials, energy, and organisms meet and interact within the stream corridor over space and time. This movement provides critical functions essential for maintaining life such as cycling nutrients, filtering contaminants from runoff, absorbing and gradually releasing floodwaters, maintaining fish and wildlife habitats, recharging ground water, and maintaining stream flows.*

The purpose of this chapter is to define the components of the stream corridor and introduce the concepts of scale and structure. The chapter is divided into three subsections.

Figure 1.1: Stream corridors function as dynamic crossroads in the landscape. *Water and other materials, energy, and organisms meet and interact within the corridor.*

Section 1.A: Physical Structure and Time at Multiple Scales

An important initial task is to identify the spatial and time scales most appropriate for planning and designing restoration. This subsection introduces elements of structure used in landscape ecology and relates them to a hierarchy of spacial scales ranging from broad to local. The importance of integrating time scales into the restoration process is also discussed.

Section 1.B: A Lateral View Across the Stream Corridor

The purpose of this and the following subsection is to introduce the types of structure found within stream corridors. The focus here is on the lateral dimension of structure, which affects the movement of water, materials, energy, and organisms from upland areas into the stream channel.

Section 1.C: A Longitudinal View Along the Stream Corridor

This section takes a longitudinal view of structure, specifically as a stream travels down the valley from headwaters to mouth. It includes discussions of channel form, sediment transport and deposition, and how biological communities have adapted to different stages of the river continuum.

1.A Physical Structure and Time at Multiple Scales

A hierarchy of five *spatial scales*, which range from broad to local, is displayed in **Figure 1.2**. Each element within the scales can be viewed as an ecosystem with links to other ecosystems. These linkages are what make an ecosystem's external environment as important to proper functioning as its internal environment (Odum 1989).

Landscapes and stream corridors are ecosystems that occur at different spatial scales. Examining them as ecosystems is useful in explaining the basics of how landscapes, watersheds, stream corridors, and streams function. Many common ecosystem functions involve movement of materials (e.g., sediment and storm water runoff), energy (e.g., heating and cooling of stream waters), and organisms (e.g., movement of mammals, fish schooling, and insect swarming) between the internal and external environments (**Figure 1.3**).

The internal/external movement model becomes more complex when one considers that the external environment of a given ecosystem is a larger ecosystem. A stream ecosystem, for example, has an input/output relationship with the next higher scale, the stream corridor. This scale, in turn, interacts with the landscape scale, and so on up the hierarchy.

Similarly, because each larger-scale ecosystem contains the one beneath it, the structure and functions of the smaller ecosystem are at least part of the structure and functions of the larger. Furthermore, what is not part of the smaller ecosystem might be related to it through input or output relationships with neighboring ecosystems. Investigating relationships between structure and scale is a key first step for planning and designing stream corridor restoration.

Physical Structure

Landscape ecologists use four basic terms to define spatial structure at a particular scale (**Figure 1.4**):

- *Matrix*, the land cover that is dominant and interconnected over the majority of the land surface. Often the matrix is forest or agriculture, but theoretically it can be any land cover type.
- *Patch*, a nonlinear area (polygon) that is less abundant than, and different from, the matrix.
- *Corridor*, a special type of patch that links other patches in the matrix. Typically, a corridor is linear or elongated in shape, such as a stream corridor.
- *Mosaic*, a collection of patches, none of which are dominant enough to be interconnected throughout the landscape.

These simple structural element concepts are repeated at different spatial scales. The size of the area and the spatial resolution of one's observations determine what structural elements one is observing. For example, at the landscape scale one might see a matrix of mature forest with patches of cropland, pasture, clear-cuts, lakes, and wetlands. Looking more closely at a smaller area, one might consider an open woodland to be a series of tree crowns (the patches) against a matrix of grassy ground cover.

On a reach scale, a trout might perceive pools and well-sheltered, cool, pockets of water as preferred patches in a matrix of less desirable shallows and riffles, and the corridor along an undercut streambank might be its only way to travel safely among these habitat patches.

FAST FORWARD

Preview Chapter 2, Section E for a discussion of the six critical functions performed by stream corridor ecosystems.

Landscapes, watersheds, stream corridors, and streams are ecosystems that occur at different spatial scales.

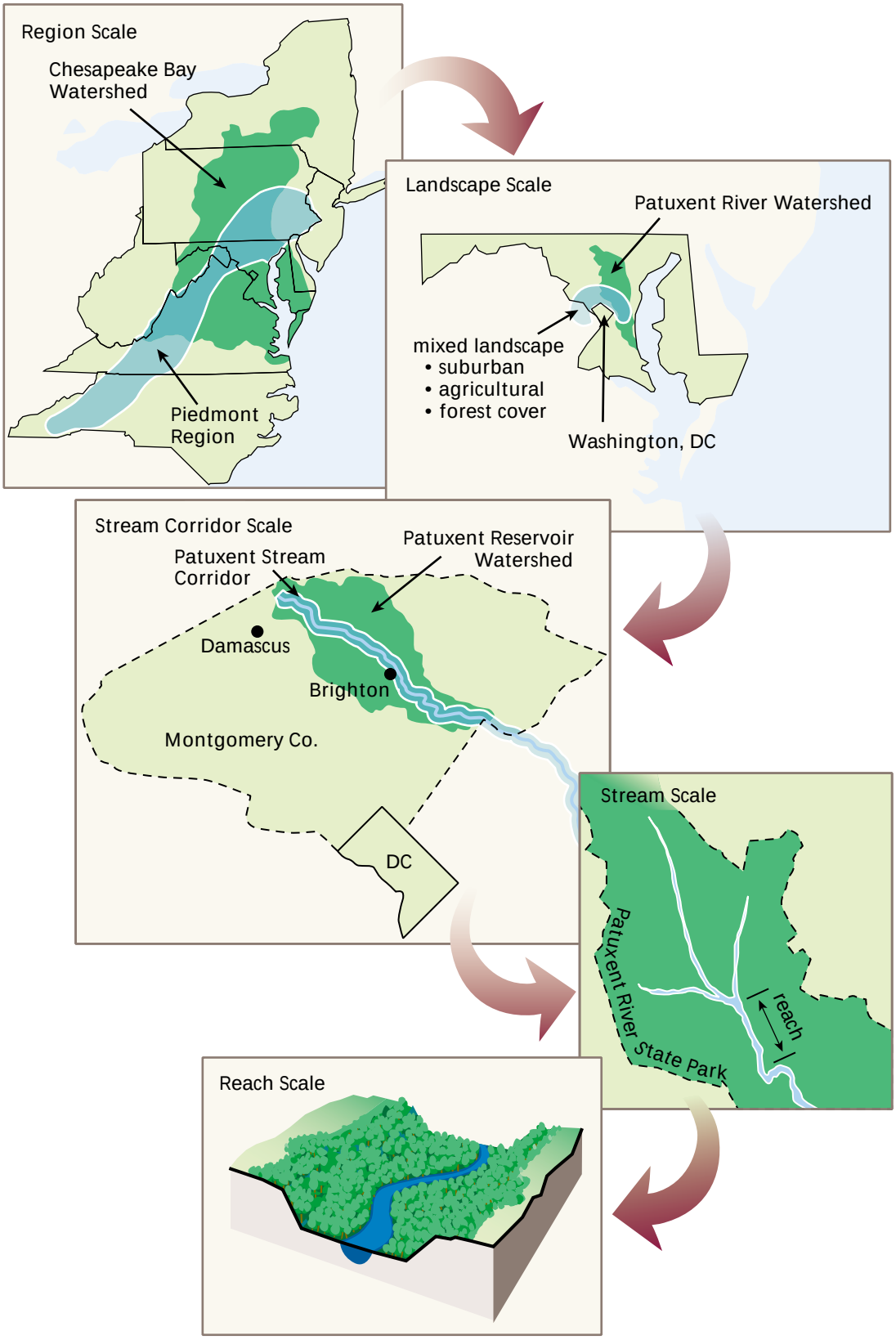


Figure 1.2: Ecosystems at multiple scales. *Stream corridor restoration can occur at any scale, from regional to reach.*

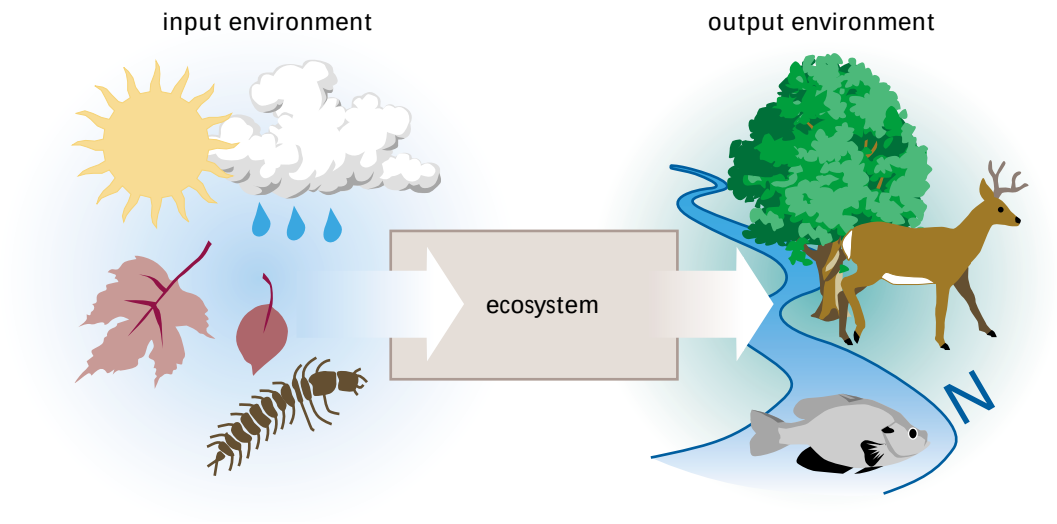


Figure 1.3: A simple ecosystem model. *Materials, energy, and organisms move from an external input environment, through the ecosystem, and into an external output environment.*

At the other extreme, the coarsest of the imaging satellites that monitor the earth's surface might detect only patches or corridors of tens of square miles in area, and matrices that seem to dominate a whole region. At all levels, the matrix-patch-corridor-mosaic model provides a useful common denominator for describing structure in the environment.

Figure 1.5 displays examples of the matrices, patches, and corridors at broad and local scales. Practitioners should always consider multiple scales when planning and designing restoration.

Structure at Scales Broader Than the Stream Corridor Scale

The landscape scale encompasses the stream corridor scale. In turn, the landscape scale is encompassed by the larger regional scale. Each scale within the hierarchy has its own characteristic structure.

The "watershed scale" is another form of spatial scale that can also encompass the stream corridor. Although watersheds occur at all scales, the term "watershed scale" is commonly used by many practitioners because many functions of the stream corridor are closely tied to drainage patterns. For this reason, the "watershed scale" is included in this discussion.

Landscape ecologists use four basic terms to define spatial structure at a particular scale—matrix, patch, corridor, and mosaic.

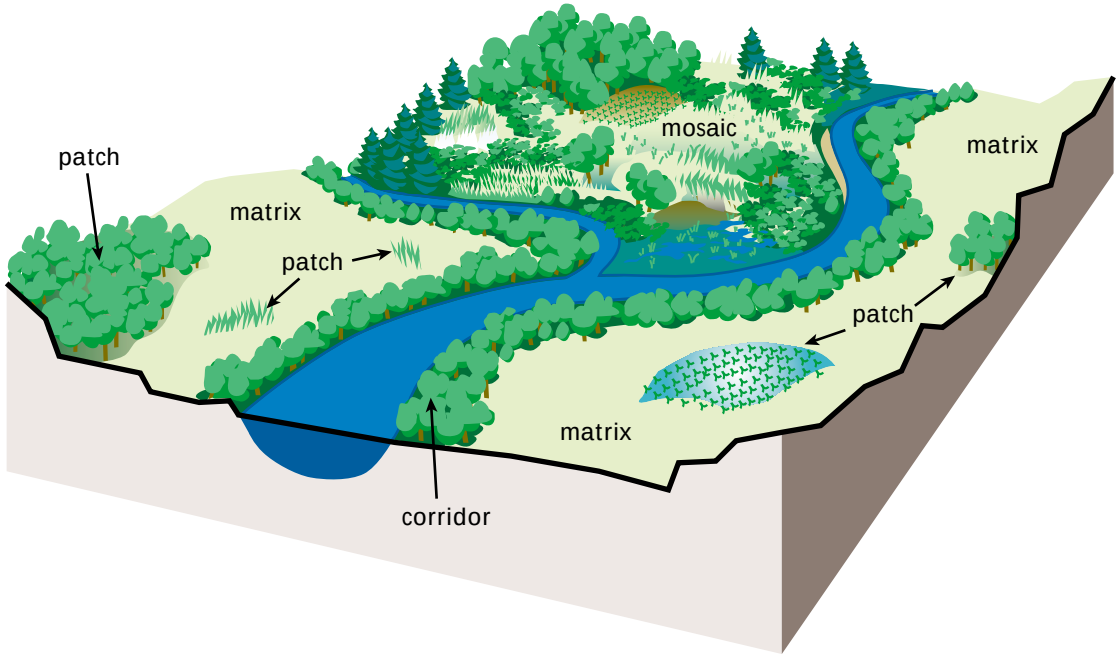
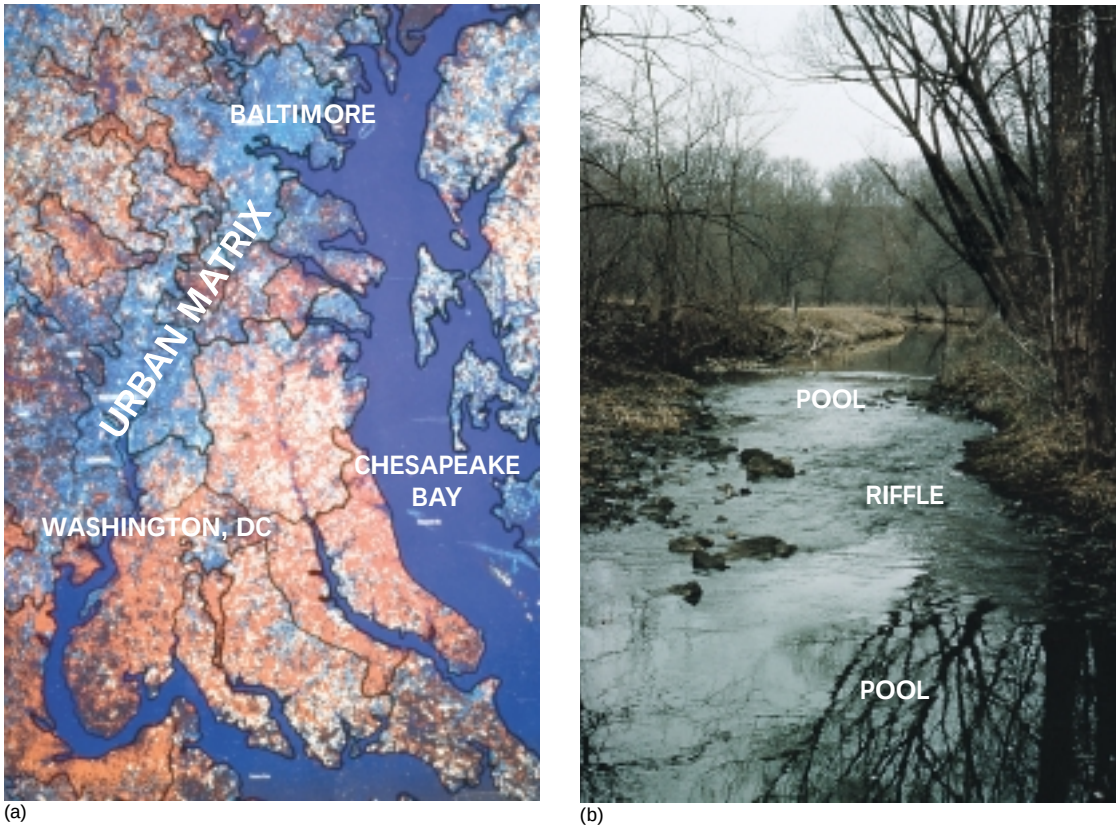


Figure 1.4: Spatial structure. *Landscapes can be described in terms of matrix, patch, corridor, and mosaic at various scales.*



(a) (b)

Figure 1.5: Spatial structure at (a) broad and (b) local scales. *Patches, corridors, and matrices are visible at the broad regional scale and the local reach scale.*

Practitioners should always consider multiple scales when planning and designing restoration.

Regional Scale

A *region* is a broad geographical area with a common macroclimate and sphere of human activities and interests (Forman 1995). The spatial elements found at the regional scale are called landscapes. **Figure 1.6** includes an example of the New England region with landscapes defined both by natural cover and by land use.

Matrices in the United States include:

- Deserts and arid grasslands of the arid Southwest.
- Forests of the Appalachian Mountains.
- Agricultural zones of the Midwest.

At the regional scale, patches generally include:

- Major lakes (e.g., the Great Lakes).
- Major wetlands (e.g., the Everglades).
- Major forested areas (e.g., redwood forests in the Pacific Northwest).
- Major metropolitan zones (e.g., the Baltimore-Washington, DC, metropolitan area).
- Major land use areas such as agriculture (e.g., the Corn Belt).

Corridors might include:

- Mountain ranges.
- Major river valleys.
- Interregional development along a major transportation corridor.

Most practitioners of stream corridor restoration do not usually plan and design restoration at the regional scale. The perspective is simply too broad for most projects. Regional scale is introduced here because it encompasses the scale very pertinent to stream corridor restoration—the landscape scale.

Landscape Scale

A *landscape* is a geographic area distinguished by a repeated pattern of components, which include both natural communities like forest patches and wetlands and human-altered areas like croplands and villages. Landscapes can vary in size from a few to several thousand square miles.

At the landscape scale, patches (e.g., wetlands and lakes) and corridors (e.g., stream corridors) are usually described as ecosystems. The matrix is usually identified in terms of the predominant natural vegetation community (e.g., prairie-type, forest-type, and wetland-type) or land-use-dominated ecosystem (e.g., agriculture and urban) (**Figure 1.7**).

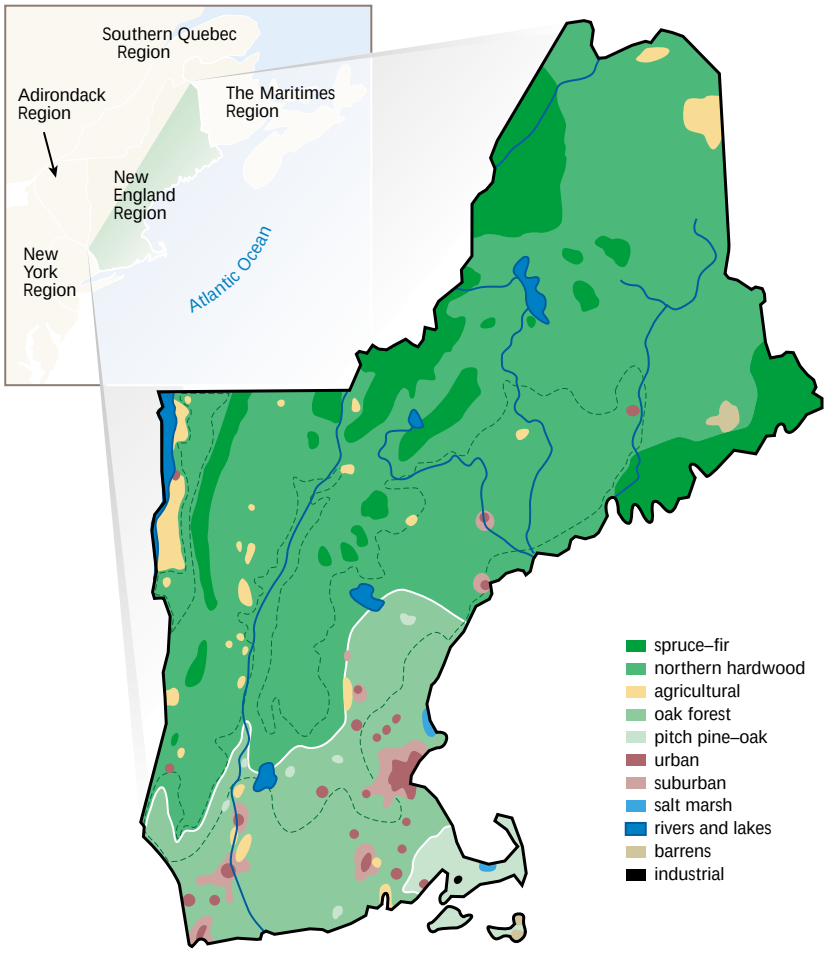
Landscapes differ from one another based on the consistent pattern formed by their structural elements, and the predominant land cover that comprises their patches, corridors, and matrices.

Examples of landscapes in the United States include:

- A highly fragmented east coast mosaic of suburban, forest, and agricultural patches.
- A north-central agricultural matrix with pothole wetlands and forest patches.
- A Sonoran desert matrix with willow-cottonwood corridors.
- A densely forested Pacific Northwest matrix with a pattern of clear-cut patches.

A landscape is a geographic area distinguished by a repeated pattern of components, which include both natural communities like forest patches and wetlands and human-altered areas like croplands and villages.

Figure 1.6: The New England region. *Structure in a region is typically a function of natural cover and land use.*
Source: Forman (1995). Reprinted with the permission of Cambridge University Press.



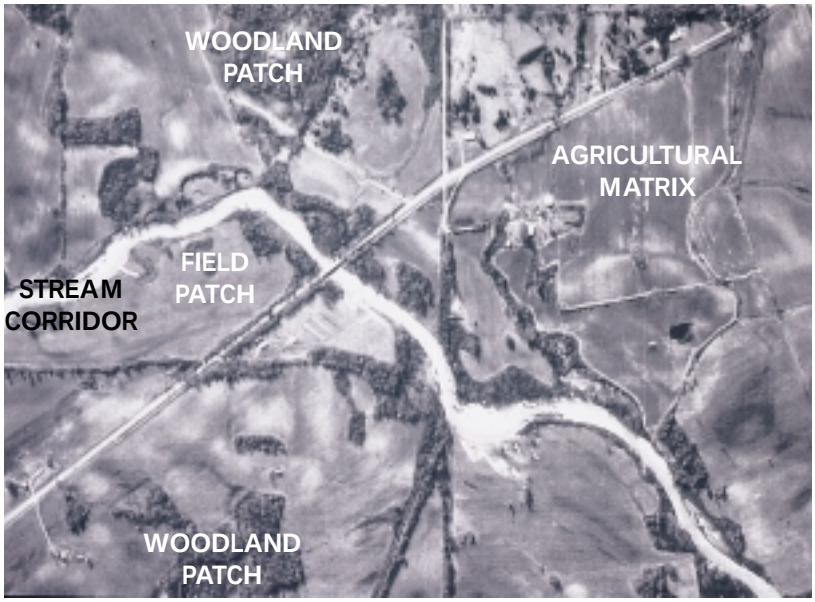


Figure 1.7: Structure at the landscape scale. *Patches and corridors are visible within an agricultural matrix.*

A woodlot within an agricultural matrix and a wetland in an urban matrix are examples of patches at the landscape scale. Corridors at this scale include ridgelines, highways, and the topic of this document—stream corridors.

At the landscape scale it is easy to perceive the stream corridor as an ecosystem with an internal environment and external environment (its surrounding landscape). Corridors play an important role at the landscape scale and at other scales. Recall that a key attribute of ecosystems is the movement of energy, materials, and organisms in, through, and out of the system. Corridors typically serve as a primary pathway for this movement. They connect patches and function as conduits between ecosystems and their external environment. Stream corridors in particular provide a heightened level of functions because of the materials and organisms found in this type of landscape linkage.

A more complete broad scale perspective of the stream corridor is achieved when watershed science is combined with landscape ecology.

Spatial structure, especially in corridors, helps dictate movement in, through, and out of the ecosystem; conversely, this movement also serves to change the structure over time. Spatial structure, as it appears at any one point in time, is therefore the end result of movement that has occurred in the past. Understanding this feedback loop between movement and structure is a key to working with ecosystems in any scale.

"Watershed Scale"

Much of the movement of material, energy, and organisms between the stream corridor and its external environments is dependent on the movement of water. Consequently, the watershed concept is a key factor for planning and designing stream corridor restoration. The term "scale," however, is incorrectly applied to watersheds.

A *watershed* is defined as an area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel (Dunne and Leopold 1978). Watersheds, therefore, occur at multiple scales. They range from the largest river basins, such as the watersheds of the Mississippi, Missouri, and Columbia, to the watersheds of very small streams that measure only a few acres in size.

The term "watershed scale" (singular) is a misnomer because watersheds occur at a very wide range of scales. This document focuses primarily on the watersheds of small to medium-scale streams and rivers. Watersheds in this size range can contain all or part of a few different landscapes or can be entirely encompassed by a larger landscape.

Ecological structure within watersheds can still be described in matrix, patch, corridor, and mosaic terms, but a discussion of watershed structure is more meaningful if it also focuses on ele-

ments such as upper, middle, and lower watershed zones; drainage divides; upper and lower hillslopes; terraces, floodplains, and deltas; and features within the channel. These elements and their related functions are discussed in sections B and C of this chapter.

In short, watersheds and landscapes overlap in size range and are defined by different environmental processes. Whereas the landscape is defined primarily by terrestrial patterns of land cover that may continue across drainage divides to where the consistent pattern ends, the watershed's boundaries are based on the drainage divides themselves. Moreover, the ecological processes occurring in watersheds are more closely linked to the presence and movement of water; therefore as functioning ecosystems, watersheds also differ from landscapes.

The difference between landscape scale and "watershed scale" is precisely why practitioners should consider both when planning and designing stream corridor restoration. For decades the watershed has served as the geographic unit of choice because it requires consideration of hydrologic and geomorphic processes associated with the movement of materials, energy, and organisms into, out of, and through the stream corridor.

The exclusive use of watersheds for the broad-scale perspective of stream corridors, however, ignores the materials, energy, and organisms that move across and through landscapes independent of water drainage. Therefore, a more complete broad-scale perspective of the stream corridor is achieved when watershed science is combined with landscape ecology.

Hydrologic Unit Cataloging and Reach File/National Hydrography Dataset

The USGS developed a national framework for cataloging watersheds of different geographical scales. Each level, or scale, in the hierarchy is designated using the hydrologic unit cataloging (HUC) system. At the national level this system involves an eight-digit code that uniquely identifies four levels of classification.

The largest unit in the USGS HUC system is the water resource region. Regions are designated by the first two digits of the code. The remaining numbers are used to further define subwatersheds within the region down to the smallest scale called the cataloging unit. For example, 10240006 is the hydrologic unit code for the Little Nemaha River in Nebraska. The code is broken down as follows:

10	*Region*
1024	*Subregion*
102400	*Accounting code*
10240006	*Cataloging unit*

There are 21 regions, 222 subregions, 352 accounting units, and 2,150 cataloging units in the United States. The USGS's Hydrologic Unit Map Series documents these hierarchical watershed boundaries for each state. Some state and federal agencies have taken the restoration initiative to subdivide the cataloging unit into even smaller watersheds, extending the HUC code to 11 or 14 digits.

The Reach File/National Hydrography Dataset (RF/NHD) is a computerized database of streams, rivers, and other water bodies in the United States. It is cross-referenced with the HUC system in a geographic information system (GIS) format so users can easily identify both watersheds and the streams contained within their boundaries.

Structure at the Stream Corridor Scale

The stream corridor is a spatial element (a corridor) at the watershed and landscape scales. But as a part of the hierarchy, it has its own set of structural elements (**Figure 1.8**). Riparian (streamside) forest or shrub cover is a common matrix in stream corridors. In other areas, herbaceous vegetation might dominate a stream corridor.

Examples of patches at the stream corridor scale include both natural and human features such as:

- Wetlands.
- Forest, shrubland, or grassland patches.
- Oxbow lakes.
- Residential or commercial development.
- Islands in the channel.
- Passive recreation areas such as picnic grounds.

Figure 1.8: Structural elements at a stream corridor scale. *Patches, corridors, and matrix are visible within the stream corridor.*

Corridors at the stream corridor scale include two important elements—the stream channel and the plant community on either side of the stream. Other examples of corridors at this scale might include:

- Streambanks
- Floodplains
- Feeder (tributary) streams
- Trails and roads

Structure Within the Stream Corridor Scale

At the stream scale, patches, corridors, and the background matrix are defined within and near the channel and include elements of the stream itself and its low floodplains (**Figure 1.9**). At the next lower scale, the stream itself is segmented into reaches.

Reaches can be distinguished in a number of ways. Sometimes they are defined by characteristics associated with flow. High-velocity flow with rapids is obviously separable from areas with slower flow and deep, quiet pools. In other instances practitioners find it useful to define reaches based on chemical or biological factors, tributary confluences, or by some human influence that makes one part of a stream different from the next.

Examples of patches at the stream and reach scales might include:

- Riffles and pools
- Woody debris
- Aquatic plant beds
- Islands and point bars

Examples of corridors might include:

- Protected areas beneath overhanging banks.

- The thalweg, the "channel within the channel" that carries water during low-flow conditions.
- Lengths of stream defined by physical, chemical, and biological similarities or differences.
- Lengths of stream defined by human-imposed boundaries such as political borders or breaks in land use or ownership.

Temporal Scale

The final scale concept critical for the planning and design of stream corridor restoration is time.

In a sense, temporal hierarchy parallels spatial hierarchy. Just as global or regional spatial scales are usually too large to be relevant for most restoration initiatives, planning and designing restoration for broad scales of time is not usually practical. Geomorphic or climatic changes, for example, usually occur over centuries to millions of years. The goals of restoration efforts, by comparison, are usually described in time frames of years to decades.

Land use change in the watershed, for example, is one of many factors that can cause disturbances in the stream corridor. It occurs on many time scales, however, from a single year (e.g., crop rotation), to decades (e.g., urbanization), to centuries (e.g., long-term forest management). Thus, it is critical for the practitioner to consider a relevant range of time scales when involving land use issues in restoration planning and design.

Flooding is another natural process that varies both in space and through time. Spring runoff is cyclical and therefore fairly predictable. Large, hurricane-induced floods that inundate lands far beyond the channel are neither cyclical nor predictable, but still should be planned for in restoration designs. Flood specialists rank the extent of floods in temporal terms such as 10-year, 100-year, and 500-year events (10%, 1%, 0.2% chance of recurrence. See Chapter 7 *Flow Frequency Analysis* for more details.). These can serve as guidance for planning and designing restoration when flooding is an issue.

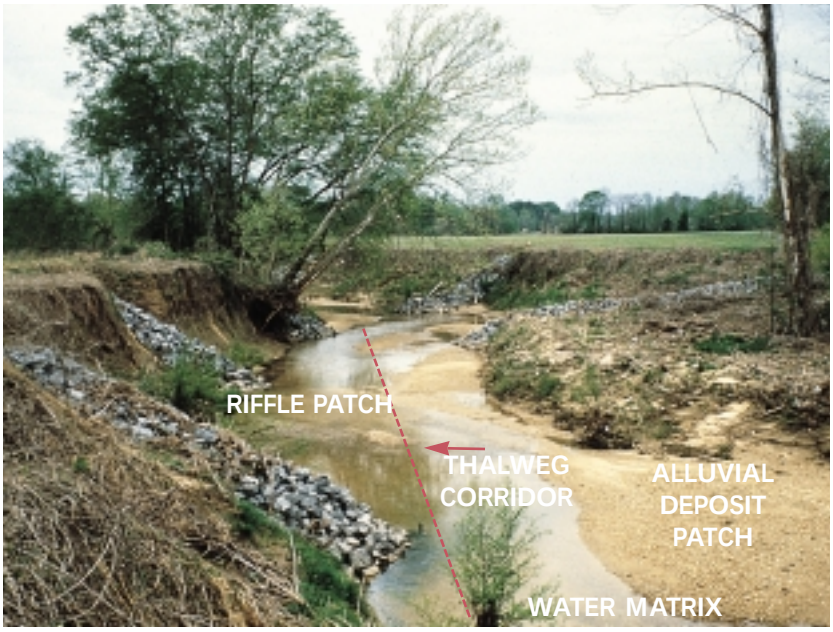


Figure 1.9: Structural elements at a stream scale. *Patches, corridors, and matrix are visible within the stream.*

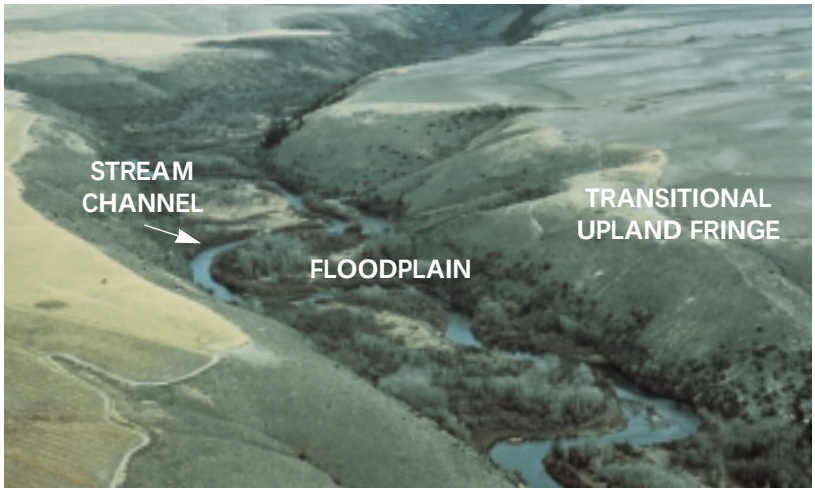
Practitioners of stream corridor restoration may need to simultaneously plan in multiple time scales. If an instream structure is planned, for example, care might be taken that (1) installation does not occur during a critical spawning period (a short-term consideration) and (2) the structure can withstand a 100-year flood (a long-term consideration). The practitioner should never try to freeze conditions as they are, at the completion of the restoration. Stream corridor restoration that works with the dynamic behavior of the stream ecosystem will more likely survive the test of time.

Stream corridor restoration that works with the dynamic behavior of the stream ecosystem will more likely survive the test of time.

1.B A Lateral View Across the Stream Corridor

The previous section described how the matrix-patch-corridor-mosaic model can be applied at multiple scales to examine the relationships between the stream corridor and its external environments. This section takes a closer look at physical structure in the stream corridor itself. In particular, this section focuses on the lateral dimension. In cross section, most stream corridors have three major components (**Figure 1.10**):

- *Stream channel*, a channel with flowing water at least part of the year.
- *Floodplain*, a highly variable area on one or both sides of the stream channel that is inundated by floodwaters at some interval, from frequent to rare.
- *Transitional upland fringe*, a portion of the upland on one or both sides of the floodplain that serves as a transitional zone or edge between the floodplain and the surrounding landscape.



(a)

(b)

Figure 1.10: The three major components of a stream corridor in different settings (a) and (b). *Even though specific features might differ by region, most stream corridors have a channel, floodplain, and transitional upland fringe.*

Some common features found in the river corridor are displayed in **Figure 1.11**. In this example the floodplain is seasonally inundated and includes features such as floodplain forest, emergent marshes and wet meadows. The transitional upland fringe includes an upland forest and a hill prairie. Landforms such as natural levees, are created by processes of erosion and sedimentation, primarily during floods. The various plant communities possess unique moisture tolerances and requirements and consequently occupy distinct landforms.

Each of the three main lateral components is described in the following subsections.

Stream Channel

Nearly all channels are formed, maintained, and altered by the water and sediment they carry. Usually they are gently rounded in shape and roughly parabolic, but form can vary greatly.

Figure 1.12 presents a cross section of a typical stream channel. The sloped bank is called a *scarp*. The deepest part of the channel is called the *thalweg*. The dimensions of a channel cross section define the amount of water that can

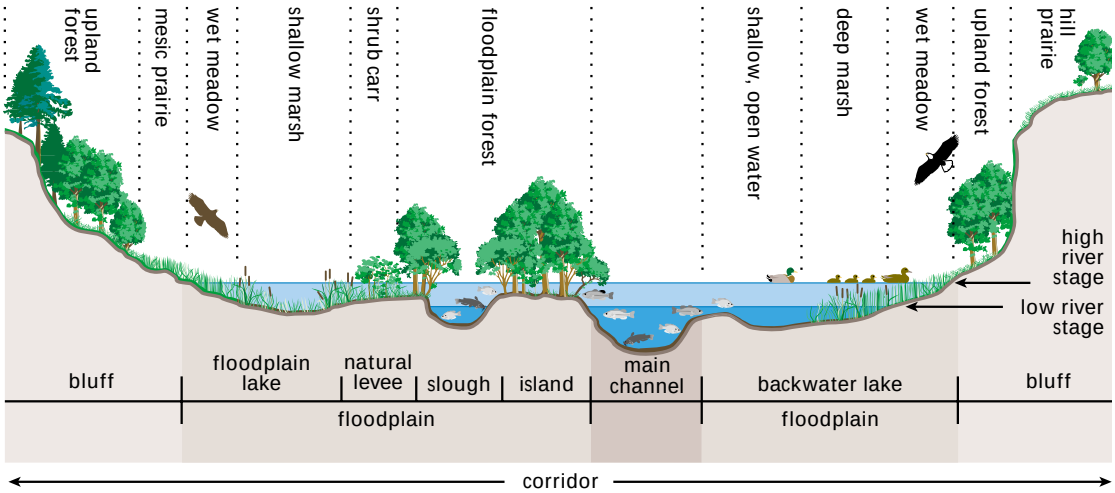


Figure 1.11: A cross section of a river corridor. *The three main components of the river corridor can be subdivided by structural features and plant communities. (Vertical scale and channel width are greatly exaggerated.)*
Source: Sparks, Bioscience, vol. 45, p. 170, March 1995. ©1995 American Institute of Biological Science.

pass through without spilling over the banks. Two attributes of the channel are of particular interest to practitioners, channel equilibrium and streamflow.

Lane's Alluvial Channel Equilibrium

Channel equilibirum involves the interplay of four basic factors:

- Sediment discharge (Q_s)
- Sediment particle size (D_{50})
- Streamflow (Q_w)
- Stream slope (S)

Lane (1955) showed this relationship qualitatively as:

$$Q_s \cdot D_{50} \propto Q_w \cdot S$$

This equation is shown here as a balance with sediment load on one weighing pan and streamflow on the other (**Figure 1.13**). The hook holding the sediment pan can slide along the horizontal arm according to sediment size. The hook holding the streamflow side slides according to stream slope.

Channel equilibrium occurs when all four variables are in balance. If a change occurs, the balance will temporarily be tipped and equilibrium lost. If one variable changes, one or more of the other variables must increase or decrease proportionally if equilibrium is to be maintained. For example, if slope is increased and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased (e.g., by an interbasin transfer) and the slope stays the same, sediment load or sediment particle size has to increase to maintain channel equilibrium. A stream seeking a new equilibrium tends to erode more sediment and of larger particle size.

Alluvial streams that are free to adjust to changes in these four variables generally do so and reestablish new equilibrium conditions. Non-alluvial streams such as bedrock or artificial, concrete channels are unable to follow Lane's relationship because of their inability to

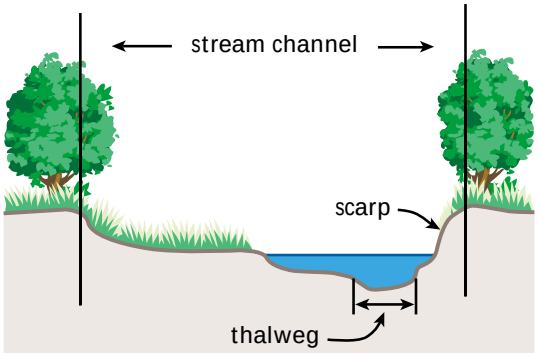


Figure 1.12: Cross section of a stream channel. *The scarp is the sloped bank and the thalweg is the lowest part of the channel.*

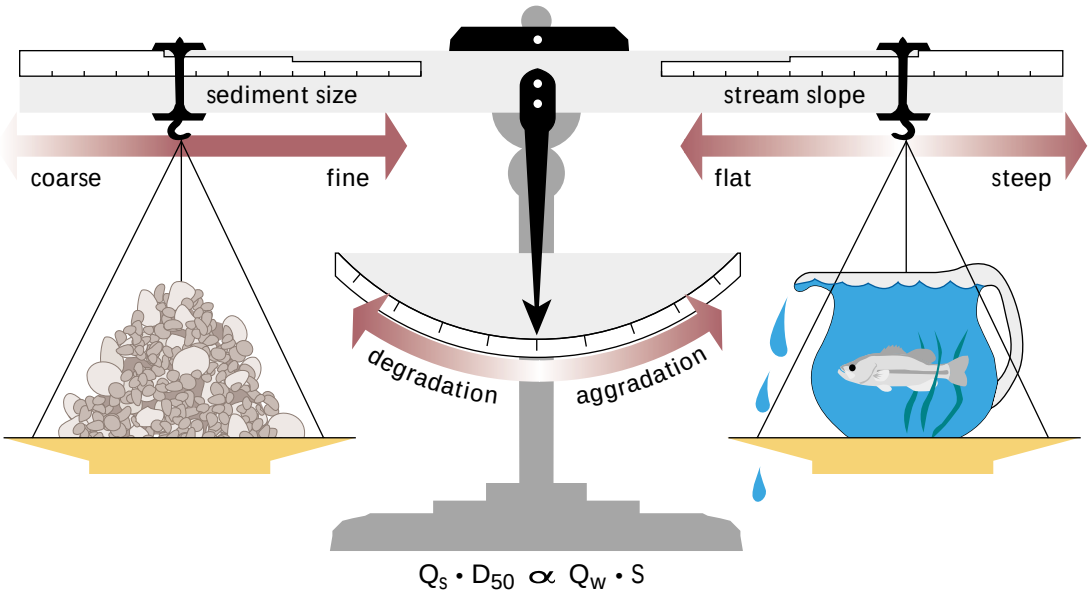


Figure 1.13: Factors affecting channel equilibrium. *At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.*

Source: Rosgen (1996), from Lane, ***Proceedings***, 1955. Published with the permission of American Society of Civil Engineers.

FAST FORWARD

Preview Chapter 2, Section B for more discussion on the stream balance equation. Preview Chapter 7, Section B for nformation on measuring and analyzing these variables and the use of sediment transport equations.

adjust the sediment size and quantity variables.

The stream balance equation is useful for making qualitative predictions concerning channel impacts due to changes in runoff or sediment loads from the watershed. Quantitative predictions, however, require the use of more complex equations.

Sediment transport equations, for example, are used to compare sediment load and energy in the stream. If excess energy is left over after the load is moved, channel adjustment occurs as the stream picks up more load by eroding its banks or scouring its bed. No matter how much complexity is built into these and other equations of this type, however, they all relate back to the basic balance relationships described by Lane.

Streamflow

A distinguishing feature of the channel is streamflow. As part of the water cycle, the ultimate source of all flow is precipitation. The pathways precipitation takes after it falls to earth, however, affect many aspects of streamflow including its quantity, quality, and timing. Practitioners usually find it useful to divide flow into components based on these pathways.

The two basic components are:

- *Stormflow*, precipitation that reaches the channel over a short time frame through overland or underground routes.
- *Baseflow*, precipitation that percolates to the ground water and moves slowly through substrate before reaching the channel. It sustains streamflow during periods of little or no precipitation.

Streamflow at any one time might consist of water from one or both sources. If neither source provides water to the channel, the stream goes dry.

A *storm hydrograph* is a tool used to show how the discharge changes with time (**Figure 1.14**). The portion of the hydrograph that lies to the left of the peak is called the *rising limb*, which shows how long it takes the stream to peak following a precipitation event. The portion of the curve to the right of the peak is called the *recession limb*.

Channel and Ground Water Relationships

Interactions between ground water and the channel vary throughout the watershed. In general, the connection is strongest in streams with gravel riverbeds in well-developed alluvial floodplains.

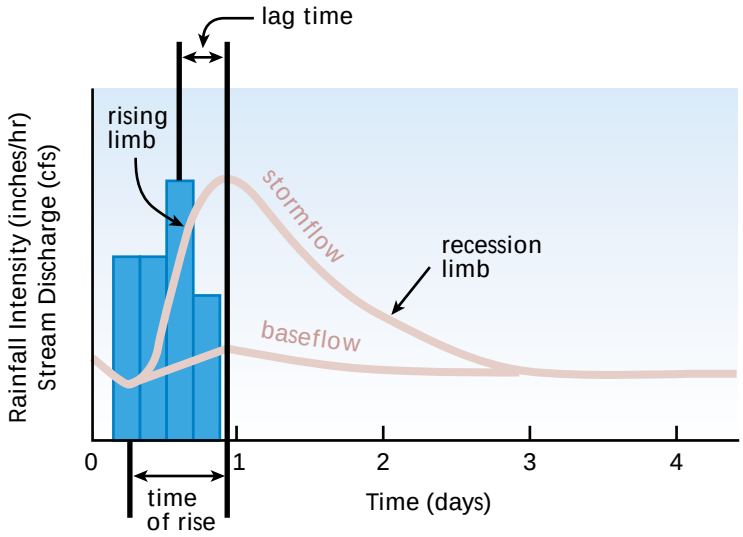


Figure 1.14: A storm hydrograph. *A hydrograph shows how long a stream takes to rise from baseflow to maximum discharge and then return to baseflow conditions.*

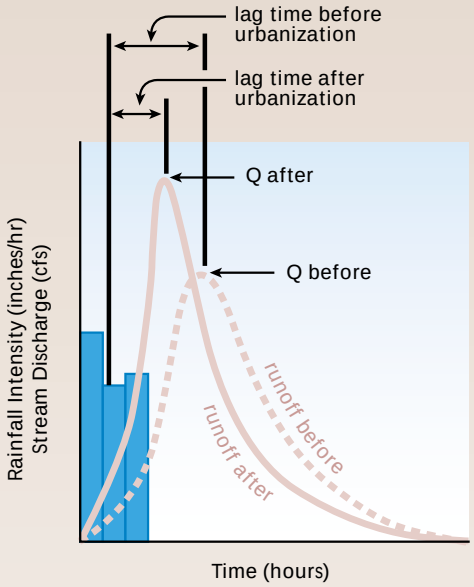


Figure 1.15: A comparison of hydrographs before and after urbanization. *The discharge curve is higher and steeper for urban streams than for natural streams.*

Change in Hydrology After Urbanization

The hydrology of urban streams changes as sites are cleared and natural vegetation is replaced by impervious cover such as rooftops, roadways, parking lots, sidewalks, and driveways. One of the consequences is that more of a stream's annual flow is delivered as storm water runoff rather than baseflow. Depending on the degree of watershed impervious cover, the annual volume of storm water runoff can increase by up to 16 times that for natural areas (Schueler 1995). In addition, since impervious cover prevents rainfall from infiltrating into the soil, less flow is available to recharge ground water. Therefore, during extended periods without rainfall, baseflow levels are often reduced in urban streams (Simmons and Reynolds 1982).

*Storm runoff moves more rapidly over smooth, hard pavement than over natural vegetation. As a result, the rising limbs of storm hydrographs become steeper and higher in urbanizing areas (**Figure 1.15**). Recession limbs also decline more steeply in urban streams.*

Figure 1.16 presents two types of water movement:

- *Influent or "losing" reaches* lose stream water to the aquifer.
- *Effluent or "gaining" reaches* receive discharges from the aquifer.

Practitioners categorize streams based on the balance and timing of the stormflow and baseflow components. There are three main categories:

- *Ephemeral streams* flow only during or immediately after periods of precipitation. They generally flow less than 30 days per year (**Figure 1.17**).
- *Intermittent streams* flow only during certain times of the year. Seasonal flow in an intermittent stream usually lasts longer than 30 days per year.
- *Perennial streams* flow continuously during both wet and dry times. Baseflow is dependably generated from the movement of ground water into the channel.

Discharge Regime

Discharge is the term used to describe the volume of water moving down the channel per unit time (**Figure 1.18**). The basic unit of measurement used in the United States to describe discharge is cubic foot per second (cfs).

Figure 1.17: An ephemeral stream. *Ephemeral streams flow only during or immediately after periods of precipitation.*

Discharge is calculated as:

$$Q = A\,V$$

where:

Q = Discharge (cfs)

A = Area through which the water is flowing in square feet

V = Average velocity in the downstream direction in feet per second

As discussed earlier in this section, streamflow is one of the variables that determine the size and shape of the channel. There are three types of characteristic discharges:

- *Channel-forming (or dominant) discharge*. If the streamflow were held constant at the channel-forming

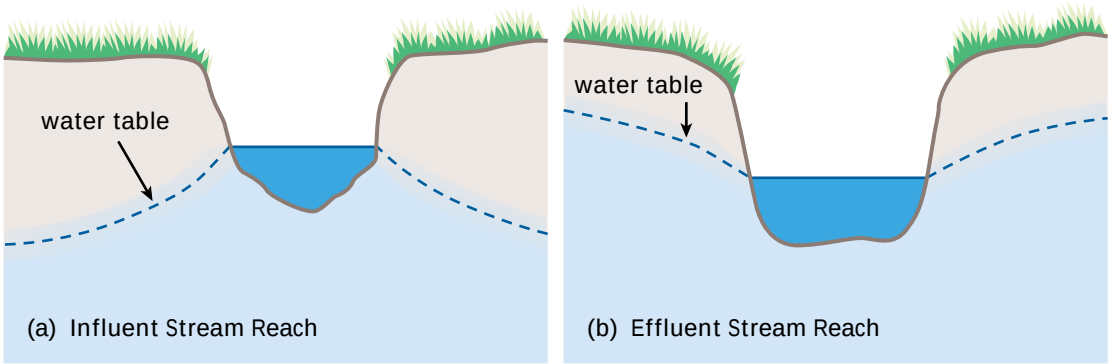
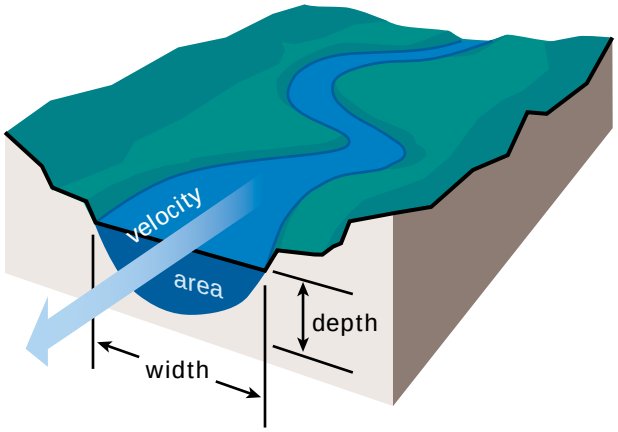


Figure 1.16: Cross sections of (a) influent and (b) effluent stream reaches. *Influent or "losing" reaches lose stream water to the aquifer. Effluent or "gaining" reaches receive discharges from the aquifer.*

discharge, it would result in channel morphology close to the existing channel. However, there is no method for directly calculating channel-forming discharge.

An estimate of channel-forming discharge for a particular stream reach can, with some qualifications, be related to depth, width, and shape of channel. Although channel-forming discharges are strictly applicable only to channels in equilibrium, the concept can be used to select appropriate channel geometry for restoring a disturbed reach.



- *Effective discharge*. The effective discharge is the calculated measure of channel-forming discharge. Computation of effective discharge requires long-term water and sediment measurements, either for the stream in question or for one very similar.

  Since this type of data is not often available for stream restoration sites, modeled or computed data are sometimes substituted. Effective discharge can be computed for either stable or evolving channels.

Bankfull discharge. This discharge occurs when water just begins to leave the channel and spread onto the floodplain (Figure 1.19). Bankfull discharge is equivalent to channel-forming (conceptual) and effective (calculated) discharge.

Figure 1.19: Bankfull discharge. This is the flow at which water begins to leave the channel and move onto the floodplain.

Channel-Forming Discharge

To envision the concept of channel-forming discharge, imagine placing a water hose discharging at constant rate in a freshly tilled garden. Eventually, a small channel will form and reach an equilibrium geometry.

At a larger scale, consider a newly constructed floodwater- retarding reservoir that slowly releases stored floodwater at a constant flow rate. This flow becomes the new channel-forming discharge and will alter channel morphology until the channel reaches equilibrium.

FAST FORWARD

Preview Chapter 7, Section B for a discussion of calculating effective discharge. This computation should be performed by a professional with a good background in hydrology, hydraulics, and sediment transport.

Floodplain

The floor of most stream valleys is relatively flat. This is because over time the stream moves back and forth across the valley floor in a process called lateral migration. In addition, periodic flooding causes sediments to move longitudinally and to be deposited on the valley floor near the channel. These two processes continually modify the floodplain.

Through time the channel reworks the entire valley floor. As the channel migrates, it maintains the same average size and shape if conditions upstream remain constant and the channel stays in equilibrium.

Two types of floodplains may be defined (**Figure 1.20**):

- *Hydrologic floodplain*, the land adjacent to the baseflow channel residing below bankfull elevation. It is inundated about two years out of three. Not every stream corridor has a hydrologic floodplain.
- *Topographic floodplain*, the land adjacent to the channel including the hydrologic floodplain and other lands up to an elevation based on the elevation reached by a flood peak of a given frequency (for example, the 100-year floodplain).

Professionals involved with flooding issues define the boundaries of a floodplain in terms of flood frequencies. Thus, 100-year and 500-year floodplains are commonly used in the development of planning and regulation standards.

Flood Storage

The floodplain provides temporary storage space for floodwaters and sediment produced by the watershed. This attribute serves to add to the *lag time* of a flood—the time between the middle of the rainfall event and the runoff peak.

If a stream's capacity for moving water and sediment is diminished, or if the sediment loads produced from the watershed become too great for the stream to transport, flooding will occur more frequently and the valley floor will begin to fill. Valley filling results in the temporary storage of sediment produced by the watershed.

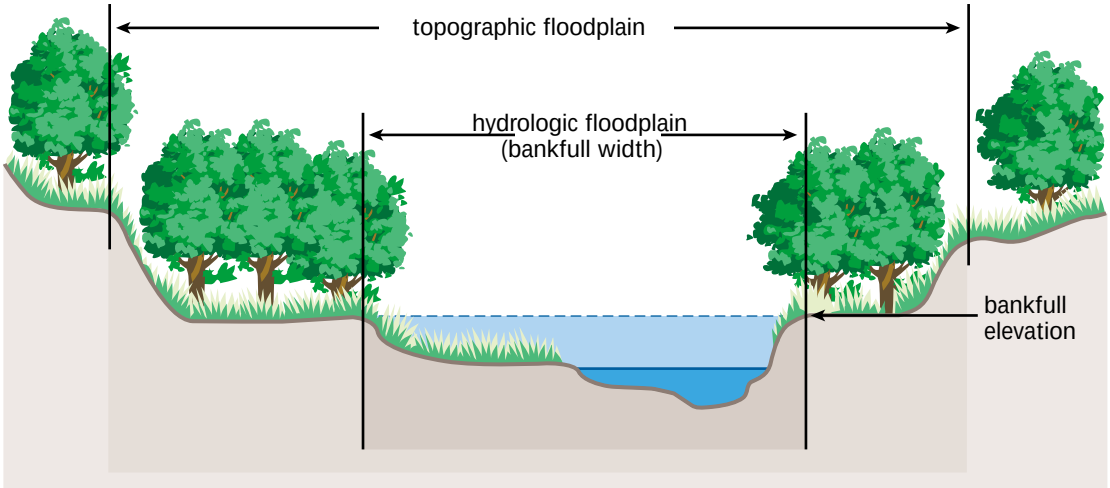


Figure 1.20: Hydrologic and topographic floodplains. *The hydrologic floodplain is defined by bankfull elevation. The topographic floodplain includes the hydrologic floodplain and other lands up to a defined elevation.*

Landforms and Deposits

Topographic features are formed on the floodplain by the lateral migration of the channel (**Figure 1.21**). These features result in varying soil and moisture conditions and provide a variety of habitat niches that support plant and animal diversity.

Floodplain landforms and deposits include:

- *Meander scroll*, a sediment formation marking former channel locations.
- *Chute*, a new channel formed across the base of a meander. As it grows in size, it carries more of the flow.
- *Oxbow*, a term used to describe the severed meander after a chute is formed.
- *Clay plug*, a soil deposit developed at the intersection of the oxbow and the new main channel.
- *Oxbow lake*, a body of water created after clay plugs the oxbow from the main channel.
- *Natural levees*, formations built up along the bank of some streams that flood. As sediment-laden water spills over the bank, the sudden loss of depth and velocity causes coarser-sized sediment to drop out of suspension and collect along the edge of the stream.
- *Splays*, delta-shaped deposits of coarser sediments that occur when a natural levee is breached. Natural levees and splays can prevent floodwaters from returning to the channel when floodwaters recede.
- *Backswamps*, a term used to describe floodplain wetlands formed by natural levees.

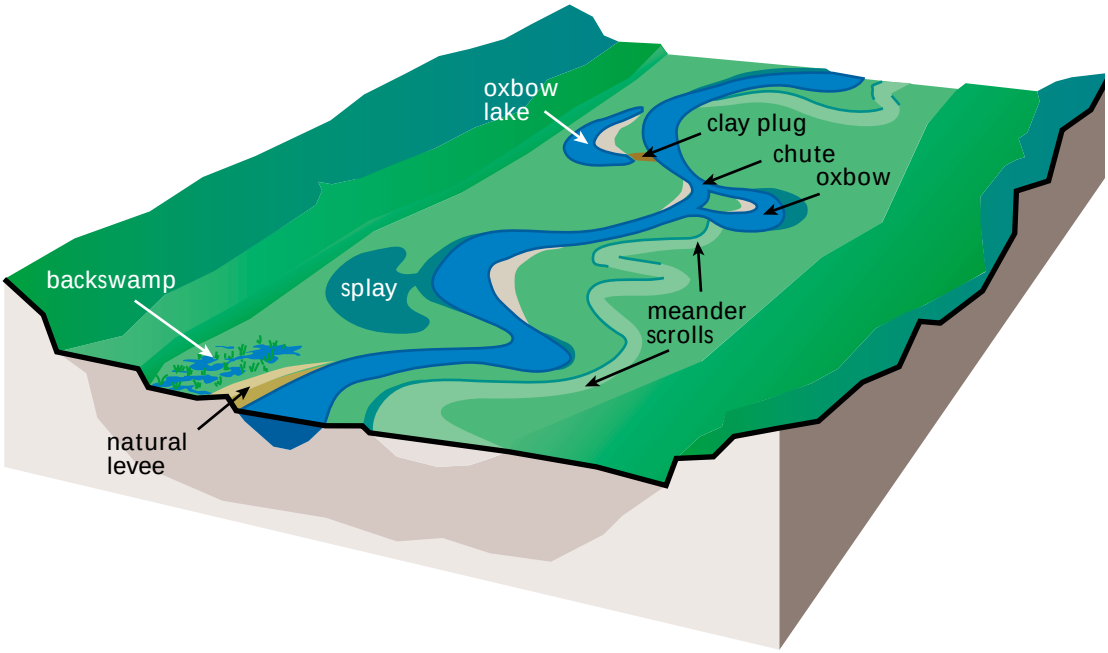


Figure 1.21: Landforms and deposits of a floodplain. *Topographic features on the floodplain caused by meandering streams.*

Transitional Upland Fringe

The transitional upland fringe serves as a transitional zone between the floodplain and surrounding landscape. Thus, its outside boundary is also the outside boundary of the stream corridor itself.

While stream-related hydrologic and geomorphic processes might have formed a portion of the transitional upland fringe in geologic times, they are not responsible for maintaining or altering its present form. Consequently, land use activities have the greatest potential to impact this component of the stream corridor.

There is no typical cross section for this component. Transitional upland fringes can be flat, sloping, or in some cases, nearly vertical (**Figure 1.22**). They can incorporate features such as hillslopes, bluffs, forests, and prairies, often modified by land use. All transitional upland fringes have one common attribute, however: they are distinguishable from the surrounding landscape by their greater connection to the floodplain and stream.

An examination of the floodplain side of the transitional upland fringe often reveals one or more benches. These landforms are called *terraces* (**Figure 1.23**). They are formed in response to new patterns of streamflow, changes in sediment size or load, or changes in watershed base level—the elevation at the watershed outlet.

Terrace formation can be explained using the aforementioned stream balance equation (Figure 1.13). When one or more variables change, equilibrium is lost, and either degradation or aggradation occurs.

Figure 1.24 presents an example of terrace formation by channel incision. Cross section A represents a nonincised channel. Due to changes in streamflow or sediment delivery, equilibrium is lost

Figure 1.22: Transitional upland fringe. *This component of the stream corridor is a transition zone between the floodplain and the surrounding landscape.*

Figure 1.23: Terraces formed by an incising stream. *Terraces are formed in response to new patterns of streamflow or sediment load in the watershed.*

and the channel degrades and widens. The original floodplain is abandoned and becomes a terrace (cross section B). The widening phase is completed when a floodplain evolves within the widened channel (cross section C).

Geomorphologists often classify landscapes by numbering surfaces from the lowest surface up to the highest surface. Surface 1 in most landscapes is the bottom of the main channel. The next highest surface, Surface 2, is the floodplain. In the case of an incising stream, Surface 3 usually is the most recently formed terrace, Surface 4 the next older terrace, and so on. The numbering system thus reflects the ages of the surfaces. The higher the number, the older the surface.

Boundaries between the numbered surfaces are usually marked by a scarp, or relatively steep surface. The scarp between a terrace and a floodplain is especially important because it helps confine floods to the valley floor. Flooding occurs much less frequently, if at all, on terraces.

Vegetation Across the Stream Corridor

Vegetation is an important and highly variable element in the stream corridor. In some minimally disturbed stream corridors, a series of plant communities might extend uninterrupted across the entire corridor. The distribution of these communities would be based on different hydrologic and soil conditions. In smaller streams the riparian vegetation might even form a canopy and enclose the channel. This and other configuration possibilities are displayed in **Figure 1.25**.

Plant communities play a significant role in determining stream corridor condition, vulnerability, and potential for (or lack of) restoration. Thus, the

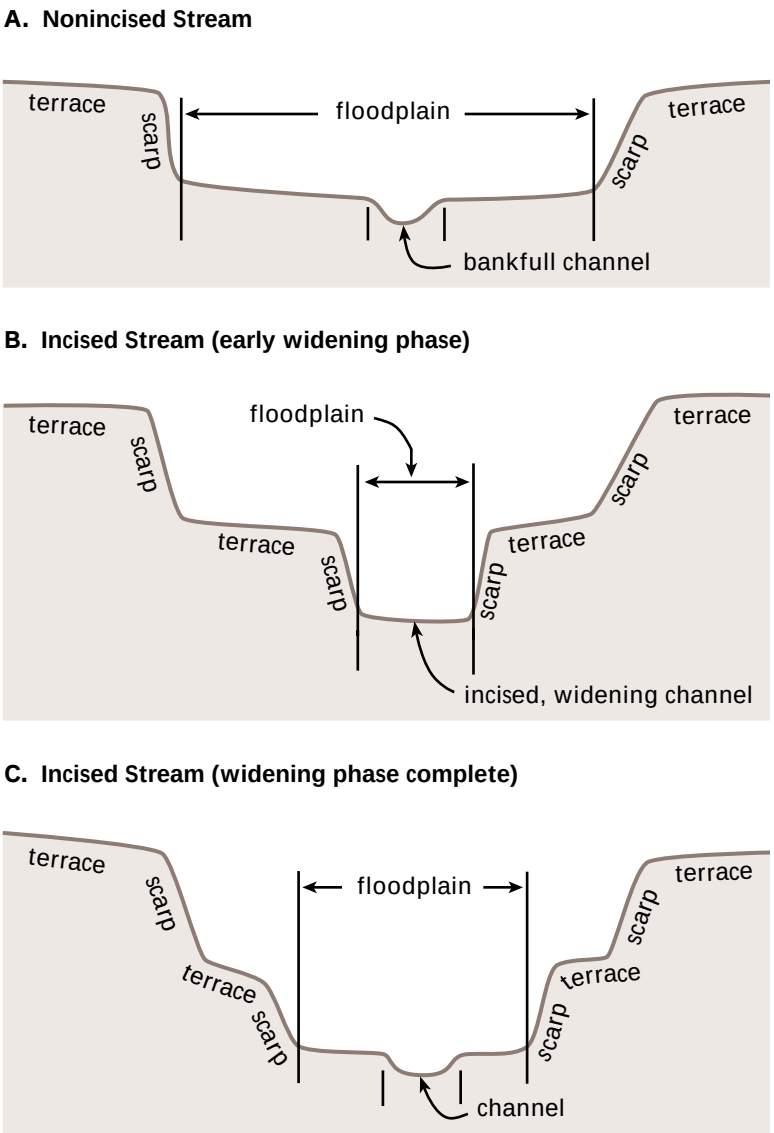


Figure 1.24: Terraces in (A) nonincised and (B and C) incised streams. *Terraces are abandoned floodplains, formed through the interplay of incising and floodplain widening.*

type, extent and distribution, soil moisture preferences, elevation, species composition, age, vigor, and rooting depth are all important characteristics that a practitioner must consider when planning and designing stream corridor restoration.

Flood-Pulse Concept

Floodplains serve as essential focal points for the growth of many riparian

FAST FORWARD

Preview Chapter 2, Section D for more information on plant community characteristics.

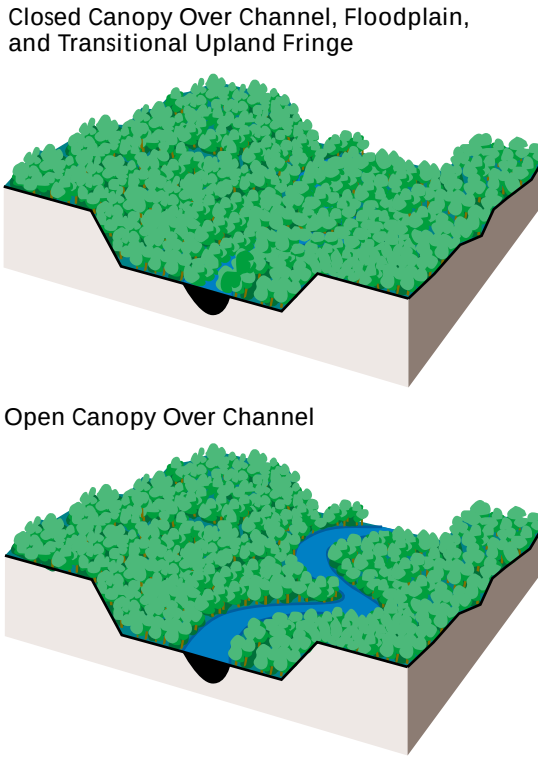


Figure 1.25: Examples of vegetation structure in the stream corridor. *Plant communities play a significant role in determining the condition and vulnerability of the stream corridor.*

plant communities and the wildlife they support. Some riparian plant species such as willows and cottonwoods depend on flooding for regeneration. Flooding also nourishes floodplains with sediments and nutrients and provides habitat for invertebrate communities, amphibians, reptiles, and fish spawning.

The flood-pulse concept was developed to summarize how the dynamic interaction between water and land is exploited by the riverine and floodplain biota (**Figure 1.26**). Applicable primarily on larger rivers, the concept demonstrates that the predictable advance and retraction of water on the floodplain in a natural setting enhances biological productivity and maintains diversity (Bayley 1995).

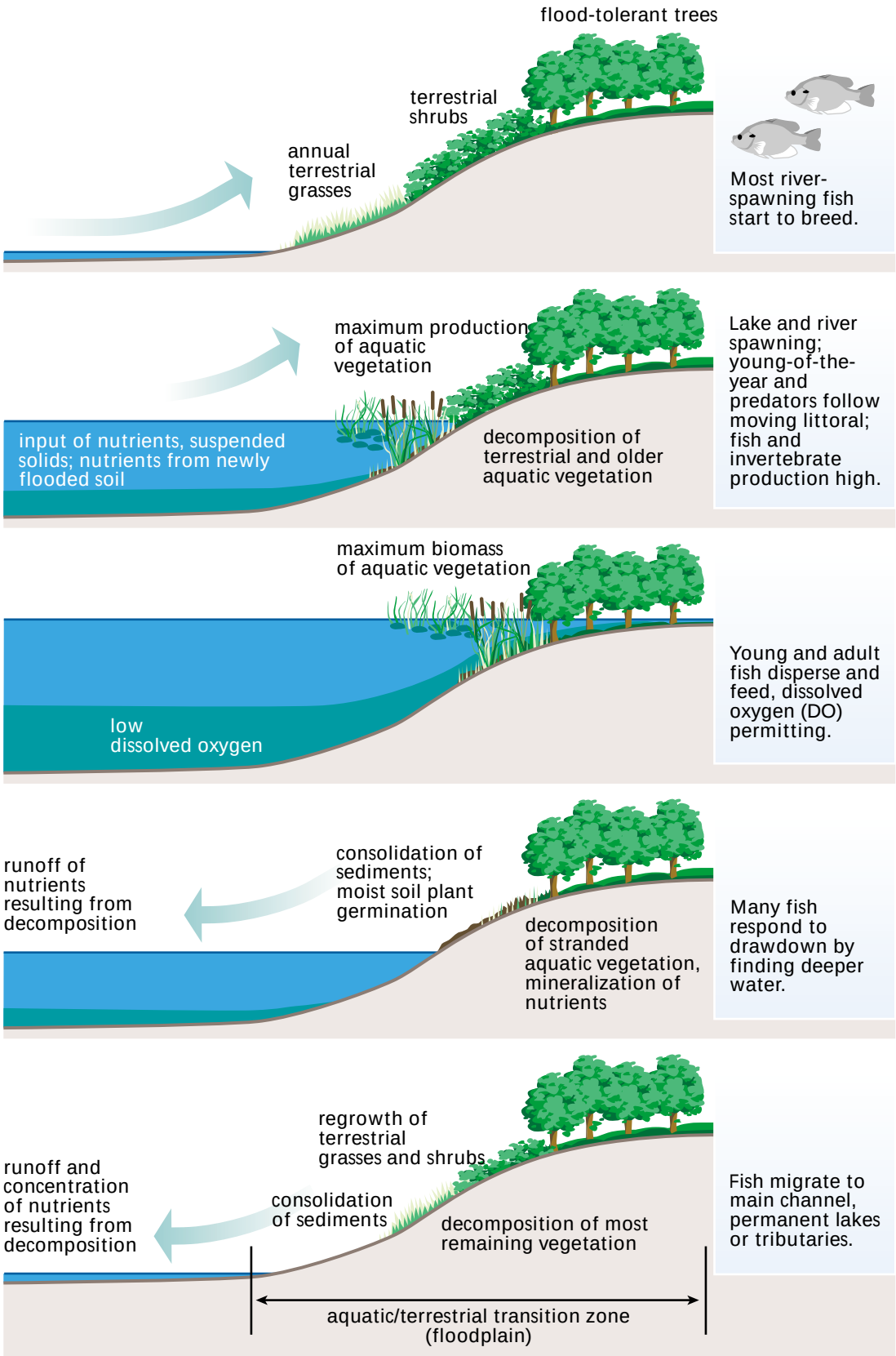


Figure 1.26: Schematic of the flood-pulse concept. *A vertically exaggerated section of a floodplain in five snapshots of an annual hydrological cycle. The left column describes the movement of nutrients. The right column describes typical life history traits of fish.*
Source: Bayley, ***Bioscience***, vol. 45, p.154, March 1995. ©1995 American Institute of Biological Science.

1.C A Longitudinal View Along the Stream Corridor

The processes that develop the characteristic structure seen in the lateral view of a stream corridor also influence structure in the longitudinal view. Channel width and depth increase downstream due to increasing drainage area and discharge. Related structural changes also occur in the channel, floodplain, and transitional upland fringe, and in processes such as erosion and deposition. Even among different types of streams, a common sequence of structural changes is observable from headwaters to mouth.

Longitudinal Zones

The overall longitudinal profile of most streams can be roughly divided into three zones (Schumm 1977). Some of the changes in the zones are characterized in **Figures 1.27** and **1.28**.

Zone 1, or headwaters, often has the steepest gradient. Sediment erodes from slopes of the watershed and moves downstream. Zone 2, the transfer zone, receives some of the eroded material. It is usually characterized by wide floodplains and meandering channel patterns. The gradient flattens in Zone 3, the primary depositional zone. Though the figure displays headwaters as mountain streams, these general patterns and changes are also often applicable to watersheds with relatively small topographic relief from the headwaters to mouth. It is important to note that erosion, transfer, and deposition occur in all zones, but the zone concept focuses on the most dominant process.

Watershed Forms

All watersheds share a common definition: a *watershed* is an "area of land that

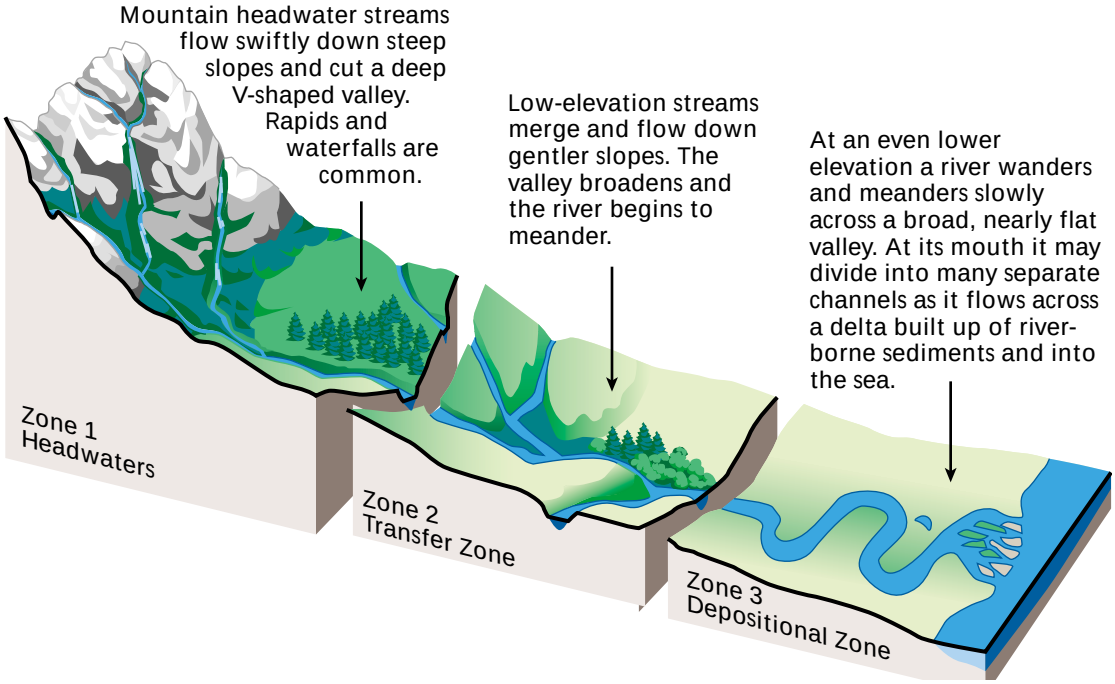


Figure 1.27: Three longitudinal profile zones. *Channel and floodplain characteristics change as rivers travel from headwaters to mouth.*
Source: Miller (1990). ©1990 Wadsworth Publishing Co.

drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel" (Dunne and Leopold 1978). Form varies greatly, however, and is tied to many factors including climatic regime, underlying geology, morphology, soils, and vegetation.

Drainage Patterns

One distinctive aspect of a watershed when observed in planform (map view) is its drainage pattern (**Figure 1.29**). Drainage patterns are primarily controlled by the overall topography and underlying geologic structure of the watershed.

Stream Ordering

A method of classifying, or ordering, the hierarchy of natural channels within a watershed was developed by Horton (1945). Several modifications of the original stream ordering scheme have

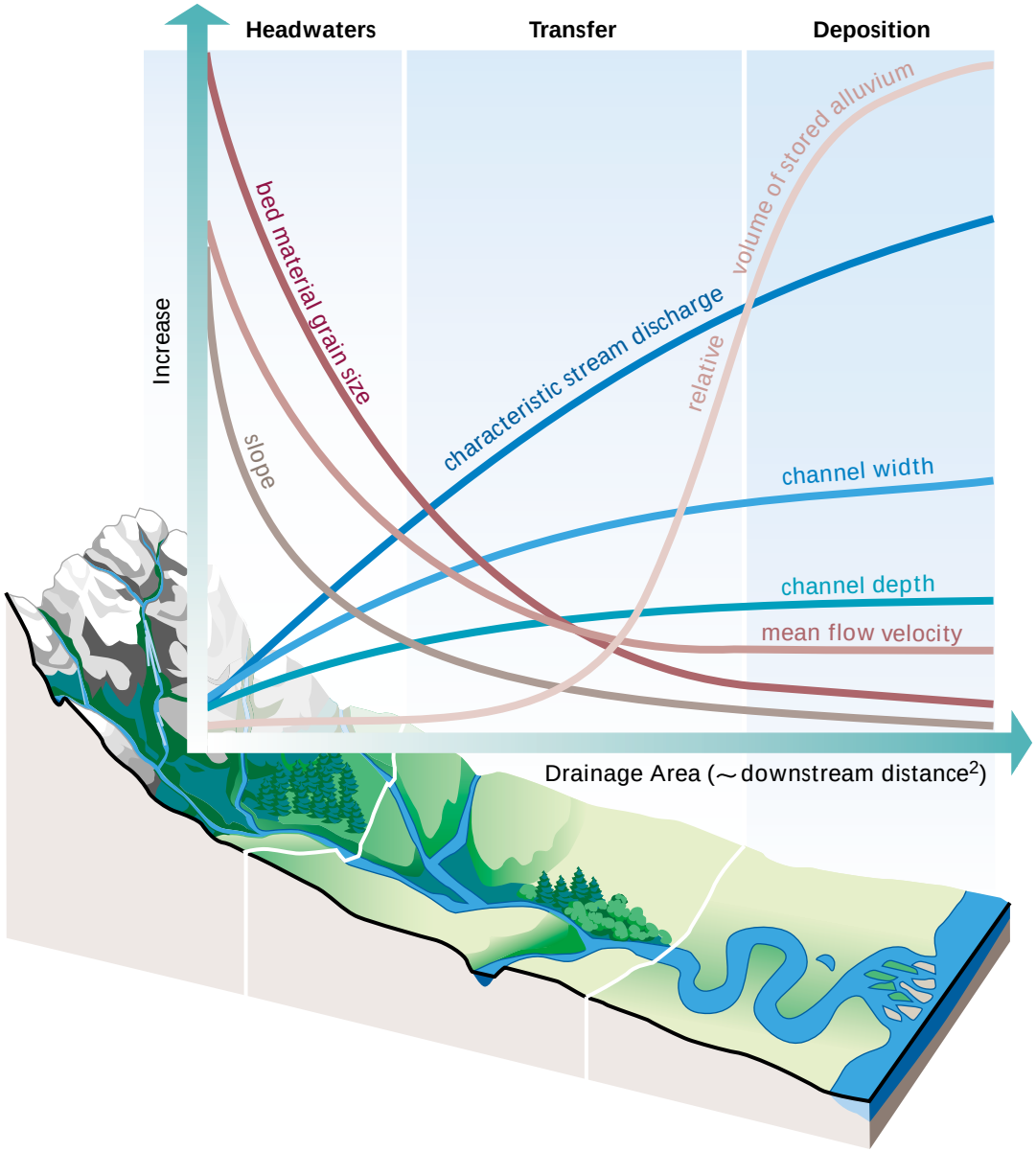


Figure 1.28: Changes in the channel in the three zones. *Flow, channel size, and sediment characteristics change throughout the longitudinal profile.*

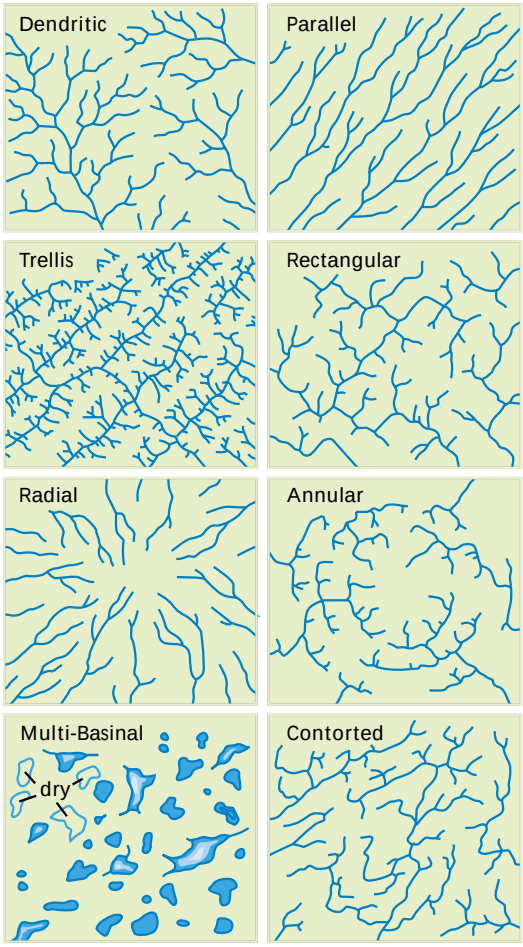


Figure 1.29: Watershed drainage patterns. *Patterns are determined by topography and geologic structure.*
Source: A.D. Howard, AAPG © 1967, reprinted by permission of the American Association of Petroleum Geologists.

been proposed, but the modified system of Strahler (1957) is probably the most popular today.

Strahler's stream ordering system is portrayed in **Figure 1.30**. The uppermost channels in a drainage network (i.e., headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on. Note in the figure that the intersection of a channel with another

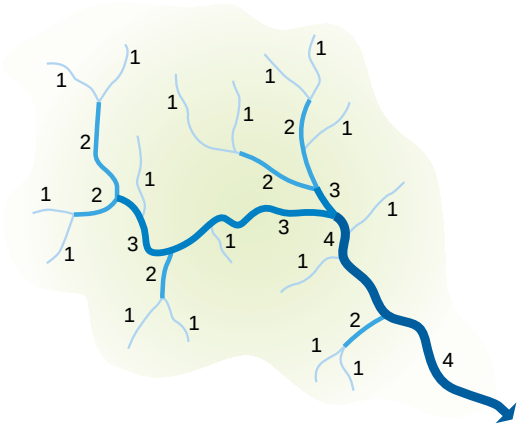


Figure 1.30: Stream ordering in a drainage network. *Stream ordering is a method of classifying the hierarchy of natural channels in a watershed.*

channel of lower order does not raise the order of the stream below the intersection (e.g., a fourth-order stream intersecting with a second-order stream is still a fourth-order stream below the intersection).

Within a given drainage basin, stream order correlates well with other basin parameters, such as drainage area or channel length. Consequently, knowing what order a stream is can provide clues concerning other characteristics such as which longitudinal zone it resides in and relative channel size and depth.

Channel Form

The form of the channel can change as it moves through the three longitudinal zones. Channel form is typically described by two characteristics—thread (single or multiple) and sinuosity.

Single- and Multiple-Thread Streams

Single-thread (one-channel) streams are most common, but multiple-thread streams occur in some landscapes (**Figure 1.31**). Multiple-thread streams are further categorized as either braided or anastomosed streams.

Three conditions tend to promote the formation of braided streams:

- Erodible banks.
- An abundance of coarse sediment.
- Rapid and frequent variations in discharge.

Braided streams typically get their start when a central sediment bar begins to form in a channel due to reduced streamflow or an increase in sediment load. The central bar causes water to flow into the two smaller cross sections on either side. The smaller cross section results in a higher velocity flow. Given erodible banks, this causes the channels to widen. As they do this, flow velocity decreases, which allows another central bar to form. The process is then repeated and more channels are created.

In landscapes where braided streams occur naturally, the plant and animal communities have adapted to frequent and rapid changes in the channel and riparian area. In cases where disturbances trigger the braiding process, however, physical conditions might be too dynamic for many species.

The second, less common category of multiple-thread channels is called *anastomosed streams*. They occur on much flatter gradients than braided streams and have channels that are narrow and deep (as opposed to the wide, shallow channels found in braided streams). Their banks are typically made up of fine, cohesive sediments, making them relatively erosion-resistant.

Anastomosed streams form when the downstream base level rises, causing a rapid buildup of sediment. Since bank materials are not easily erodible, the original single-thread stream breaks up into multiple channels. Streams entering deltas in a lake or bay are often anastomosed. Streams on alluvial fans, in contrast, can be braided or anastomosed.

Sinuosity

Natural channels are rarely straight. Sinuosity is a term indicating the amount of curvature in the channel (**Figure 1.32**). The *sinuosity* of a reach is computed by dividing the channel

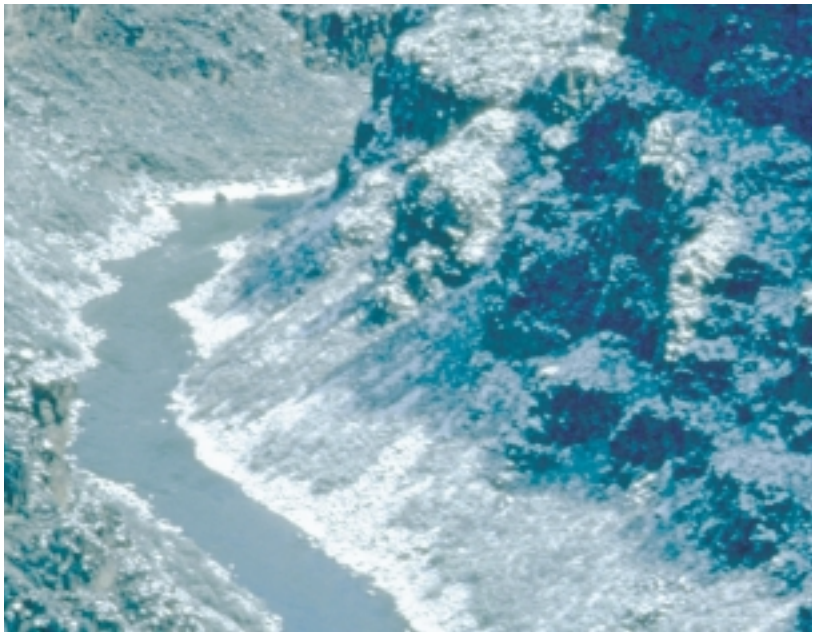
(a)

(b)

Figure 1.31: (a) Single-thread and (b) braided streams. *Single-thread streams are most common. Braided streams are uncommon and usually formed in response to erodible banks, an abundance of coarse sediment, and rapid and frequent variations in discharge.*

centerline length by the length of the valley centerline. If the channel length/valley length ratio is more than about 1.3, the stream can be considered meandering in form.

Sinuosity is generally related to the product of discharge and gradient.



(a)

(b)

Figure 1.32: Sinuosity: (a) low and (b) extreme. *Low to moderately sinuous streams are usually found in Zones 1 and 2 of the longitudinal profile. Extremely sinuous streams are more typical of Zone 3.*

Low to moderate levels of sinuosity are typically found in Zones 1 and 2 of the longitudinal profile. Extremely sinuous streams often occur in the broad, flat valleys of Zone 3.

Pools and Riffles

No matter the channel form, most streams share a similar attribute of alternating, regularly spaced, deep and shallow areas called *pools* and *riffles* (**Figure 1.33**). The pools and riffles are associated with the thalweg, which meanders within the channel. Pools typically form in the thalweg near the outside bank of bends. Riffle areas usually form between two bends at the point where the thalweg crosses over from one side of the channel to the other.

The makeup of the streambed plays a role in determining pool and riffle characteristics. Gravel and cobble-bed streams typically have regularly spaced pools and riffles that help maintain channel stability in a high-energy environment. Coarser sediment particles are found in riffle areas while smaller particles occur in pools. The pool-to-pool or riffle-to-riffle spacing is normally about 5 to 7 times the channel width at bankfull discharge (Leopold et al. 1964).

Sand-bed streams, on the other hand, do not form true riffles since the grain size distribution in the riffle area is similar to that in the pools. However, sand-bed streams do have evenly spaced pools. High-gradient streams also usually have pools but not riffles, but for a different reason. In this case, water moves from pool to pool in a stairstep fashion.

Vegetation Along the Stream Corridor

Vegetation is an important and highly variable element in the longitudinal as well as the lateral view. Floodplains are narrow or nonexistent in Zone 1 of the longitudinal profile; thus flood-dependent or tolerant plant communities tend to be limited in distribution. Upland plant communities, such as forests on moderate to steep slopes in the eastern or northwestern United States, might come close to bordering the stream and create a canopy that leaves little open sky visible from the channel. In other parts of the country, headwaters in flatter terrain may support plant communities dominated by grasses and broad-leaved herbs, shrubs, or planted vegetation.

Despite the variation in plant community type, many headwaters areas provide organic matter from vegetation along with the sediment they export to Zones 2 and 3 downstream. For example, logs and woody debris from headwaters forests are among the most ecologically important features supporting food chains and instream habitat structure in Pacific Northwest rivers from the mountains to the sea (Maser and Sedell 1994).

Zone 2 has a wider and more complex floodplain and larger channel than Zone 1. Plant communities associated with floodplains at different elevations might vary due to differences in soil type, flooding frequency, and soil moisture. Localized differences in erosion and deposition of sediment add complexity and diversity to the types of plant communities that become established.

The lower gradient, larger stream size, and less steep terrain in Zone 2 often attract more agricultural or residential development than in the headwaters

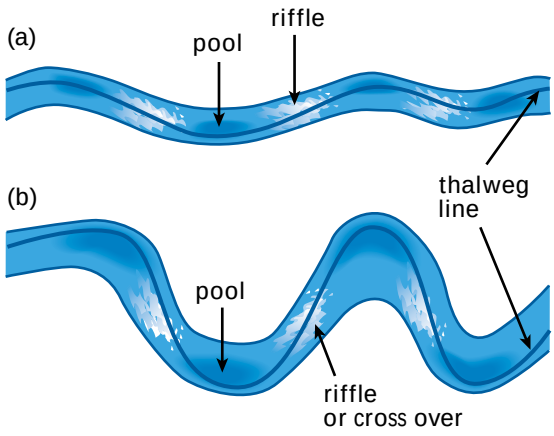


Figure 1.33: Sequence of pools and riffles in (a) straight and (b) sinuous streams. *Pools typically form on the outside bank of bends and riffles in the straight portion of the channel where the thalweg crosses over from one side to the other.*

zone. This phenomenon frequently counteracts the natural tendency to develop broad and diverse stream corridor plant communities in the middle and lower reaches. This is especially true when land uses involve clearing the native vegetation and narrowing the corridor.

Often, a native plant community is replaced by a planted vegetation community such as agricultural crops or residential lawns. In such cases, stream processes involving flooding, erosion/deposition, import or export of organic matter and sediment, stream corridor habitat diversity, and water quality characteristics are usually significantly altered.

The lower gradient, increased sediment deposition, broader floodplains, and greater water volume in Zone 3 all set the stage for plant communities different from those found in either upstream zone. Large floodplain wetlands become prevalent because of the generally flatter terrain. Highly productive and diverse biological communities,

such as bottomland hardwoods, establish themselves in the deep, rich alluvial soils of the floodplain. The slower flow in the channel also allows emergent marsh vegetation, rooted floating or free-floating plants, and submerged aquatic beds to thrive.

The changing sequence of plant communities along streams from source to mouth is an important source of biodiversity and resiliency to change. Although many, or perhaps most, of a stream corridor's plant communities might be fragmented, a continuous corridor of native plant communities is desirable. Restoring vegetative connectivity in even a portion of a stream will usually improve conditions and increase its beneficial functions.

The River Continuum Concept

The River Continuum Concept is an attempt to generalize and explain longitudinal changes in stream ecosystems (**Figure 1.34**) (Vannote et al. 1980). This conceptual model not only helps to identify connections between the watershed, floodplain, and stream systems, but it also describes how biological communities develop and change from the headwaters to the mouth. The River Continuum Concept can place a site or reach in context within a larger watershed or landscape and thus help practitioners define and focus restoration goals.

The River Continuum Concept hypothesizes that many first- to third-order headwater streams are shaded by the riparian forest canopy. This shading, in turn, limits the growth of algae, periphyton, and other aquatic plants. Since energy cannot be created through photosynthesis (autotrophic production), the aquatic biota in these small streams is dependent on *allochthonous* materials (i.e., materials coming from outside the channel such as leaves and twigs). Biological communities are uniquely adapted to use externally derived organic inputs. Consequently, these headwater streams are considered *heterotrophic* (i.e., dependent on the energy produced in the surrounding watershed). Temperature regimes are also relatively stable due to the influence of ground water recharge, which tends to reduce biological diversity to those species with relatively narrow thermal niches.

Predictable changes occur as one proceeds downstream to fourth-, fifth-, and sixth-order streams. The channel widens, which increases the amount of incident sunlight and average temperatures. Levels of primary production increase in response to increases in light, which shifts many streams to a dependence on *autochthonous* materials (i.e., materials coming from inside the channel), or internal autotrophic production (Minshall 1978).

In addition, smaller, preprocessed organic particles are received from upstream sections, which serves to balance autotrophy and heterotrophy within the stream. Species richness of the invertebrate community increases as a variety of new habitat and food resources appear. Invertebrate functional groups, such as the grazers and collectors, increase in abundance as they adapt to using both autochthonous and allochthonous food resources. Midsized streams also decrease in thermal stability as temperature fluctuations increase, which further tends to increase biotic diversity by increasing the number of thermal niches.

Larger streams and rivers of seventh to twelfth order tend to increase in physical stability, but undergo significant changes in structure and biological function. Larger streams develop increased reliance on primary productivity by

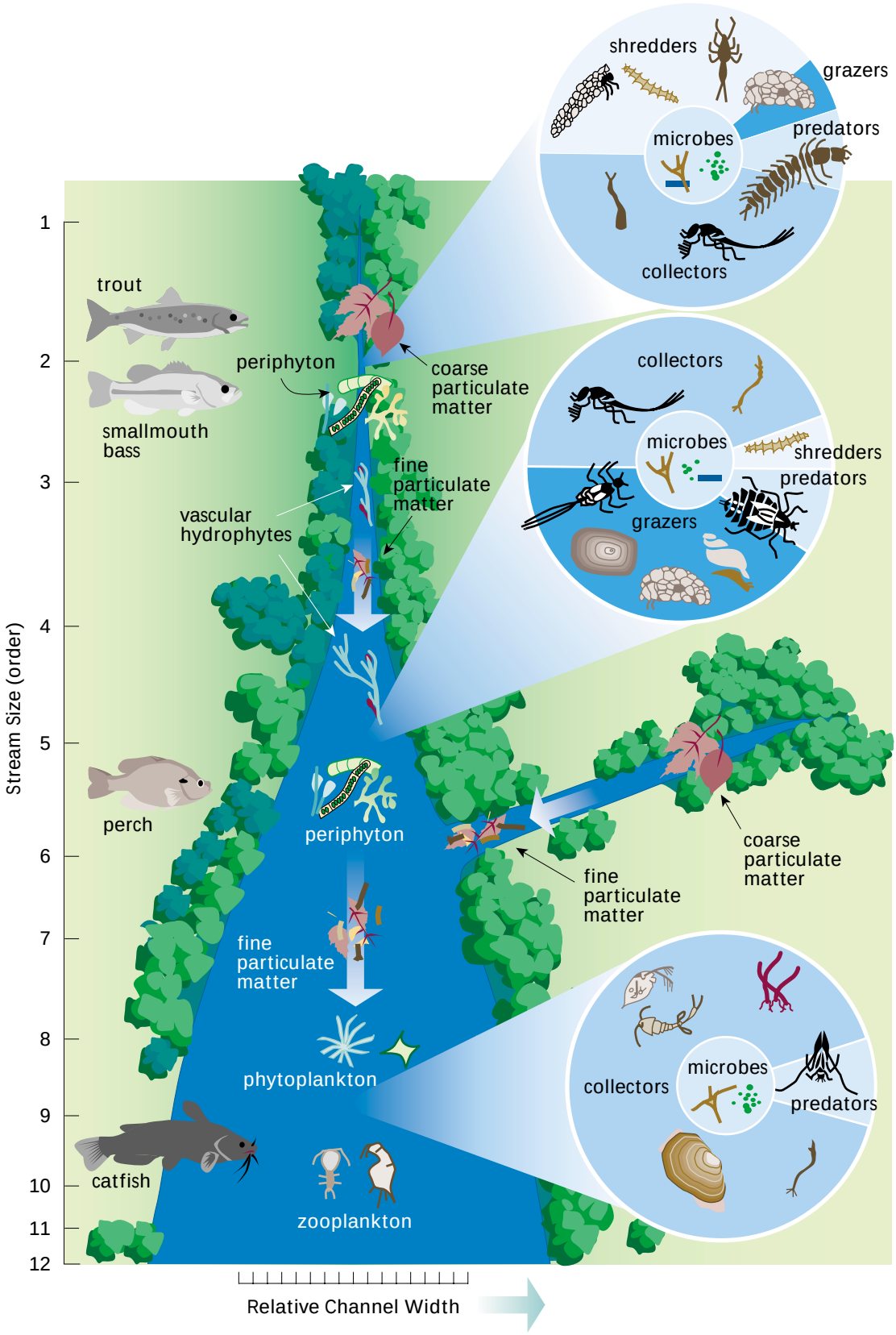


Figure 1.34: The River Continuum Concept. *The concept proposes a relationship between stream size and the progressive shift in structural and functional attributes.*
Source: Vannote et al. (1980). Published with the permission of NRC Research Press.

phytoplankton, but continue to receive heavy inputs of dissolved and ultra-fine organic particles from upstream. Invertebrate populations are dominated by fine-particle collectors, including zooplankton. Large streams frequently carry increased loads of clays and fine silts, which increase turbidity, decrease light penetration, and thus increase the significance of heterotrophic processes.

The influence of storm events and thermal fluctuations decrease in frequency and magnitude, which increases the overall physical stability of the stream. This stability increases the strength of biological interactions, such as competition and predation, which tends to eliminate less competitive taxa and thereby reduce species richness.

The fact that the River Continuum Concept applies only to perennial streams is a limitation. Another limitation is that disturbances and their impacts on the river continuum are not addressed by the model. Disturbances can disrupt the connections between the watershed and its streams and the river continuum as well.

The River Continuum Concept has not received universal acceptance due to these and other reasons (Statzner and Higler 1985, Junk et al. 1989). Nevertheless, it has served as a useful conceptual model and stimulated much research since it was first introduced in 1980.