STREAM CORRIDOR RESTORATION

Principles, Processes, and Practices

Stream Corridor Restoration Handbook

ADDENDA

The following edits have been made to the document, as of 08/07/2001. Let us know of other edits.

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Page number	Figure or table number	Edits made	Download revised pages
1-13,14	text	"Channel Size" section edited for clarity. Fig. 1.13 caption edited.	Download
1-18	Fig. 1.20	Added "bankfull width" to hydrologic floodplain label.	Download
1-31	Fig. 1.34	In graphic, "course" changed to "coarse"	Download
2-19	text	"higher" depths changed to "greater" depths.	Download
2-20	Fig. 2.15	sediment load is	Download
2-22	equation, text	Fourth equation should be "$Q_w^- Q_s^+ =$", not "$Q_w^+ Q_s^+ =$". Streams are "concave in upstream direction."	Download
2-24	text	Last sentence changed to "figure on following page" not "preceeding".	Download
2-31	text	First sent., "water" changed to "acid."	Download
2-54	Fig. 2.30	In graphic, "alder-walnut" changed to "alder-willow"	Download
2-64	Fig. 2.33	In graphic, "course" changed to "coarse."	Download
2-72	text	"Hyphorheic" changed to "hyporheic." Inorganic substrates tend to be "of larger size upstream"...	Download
2-73	text and Fig. 2.35	"Hyphorheic" changed to "hyporheic"	Download
2-84	text	Deleted 2-83 col. 1.	Download
2-86	text	Col. 2, bull. 3 revised.	Download
4-25	Fig. 4.13	Caption is for Hoover Dam, not Glen Canyon Dam.	Download
7-45	Fig. 7.20	X axis should be "Drainage Area - Square Miles", not Mean Annual Discharge.	Download
7-58	Fig. 7.29	Downloadable images corrected "sandy impervious" to pervious.	-
7-85	Table 7.9	References corrected. Poff corrected. "Simon and" Hupp.	Download
8-39	Table 8.3	Footnote for "k sub 4***" should be 0.0418, not 0.2418	Download
8-51	text	Equation exponent should be -0.872, not -0.0872	Download
Appendix A 25-30	numbering	Techniques appendix references numbers have been resolved.	Download
References	-	References added for text citations. 32 pages.	Download

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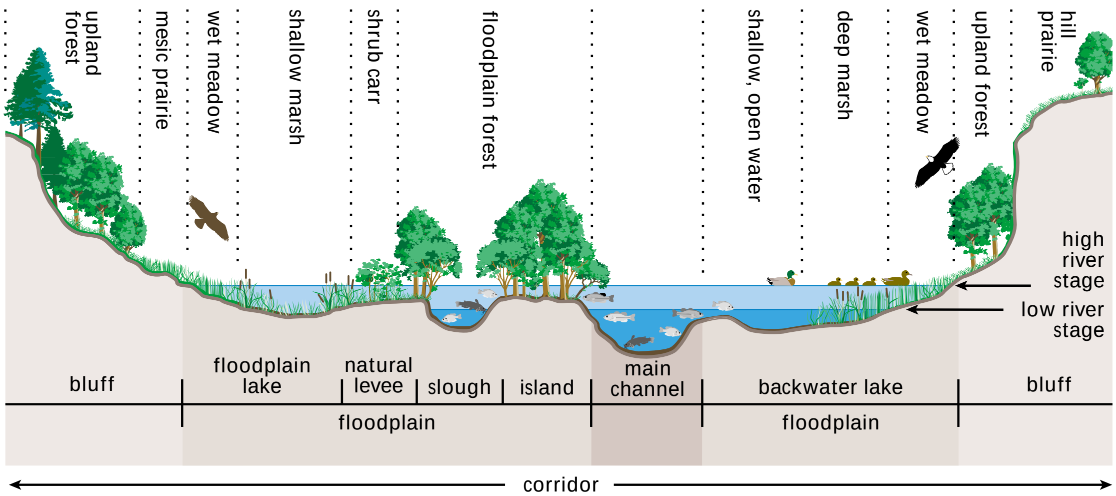


Figure 1.11: A cross section of a river corridor. *The three main components of the river corridor can be subdivided by structural features and plant communities. (Vertical scale and channel width are greatly exaggerated.)*

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

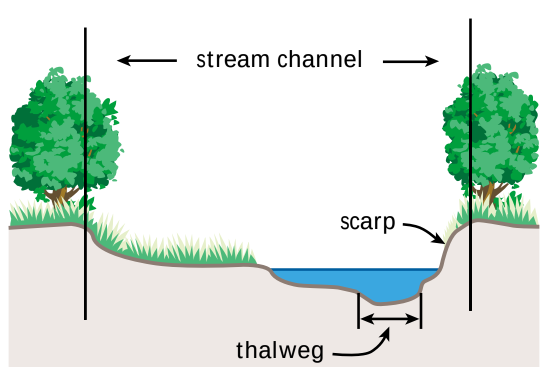


Figure 1.12: Cross section of a stream channel. *The scarp is the sloped bank and the thalweg is the lowest part of the channel.*

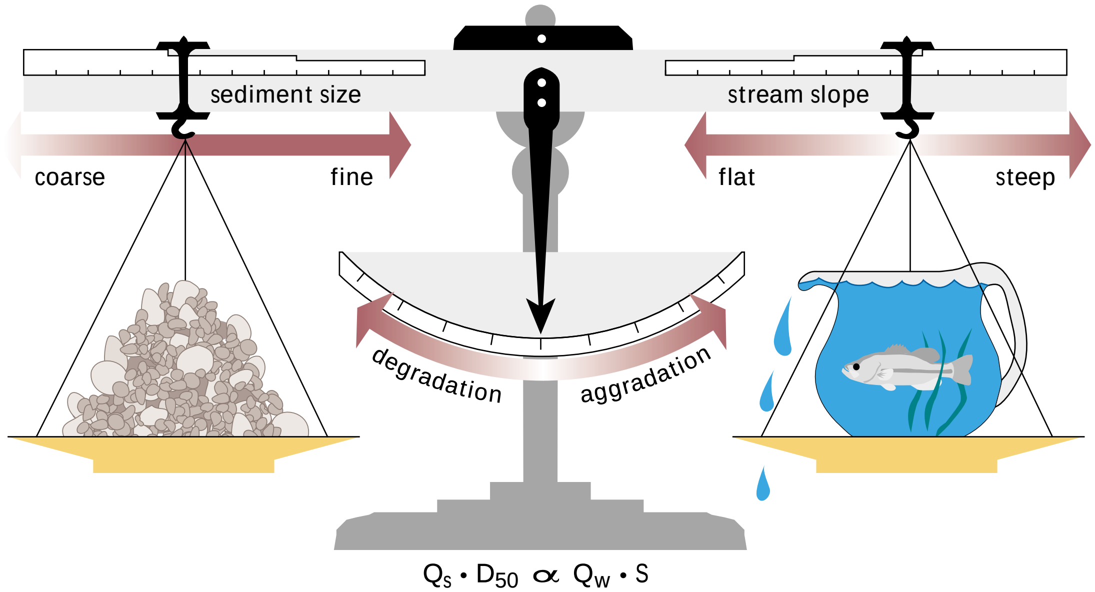


Figure 1.13: Factors affecting channel equilibrium. *At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.*

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.

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.

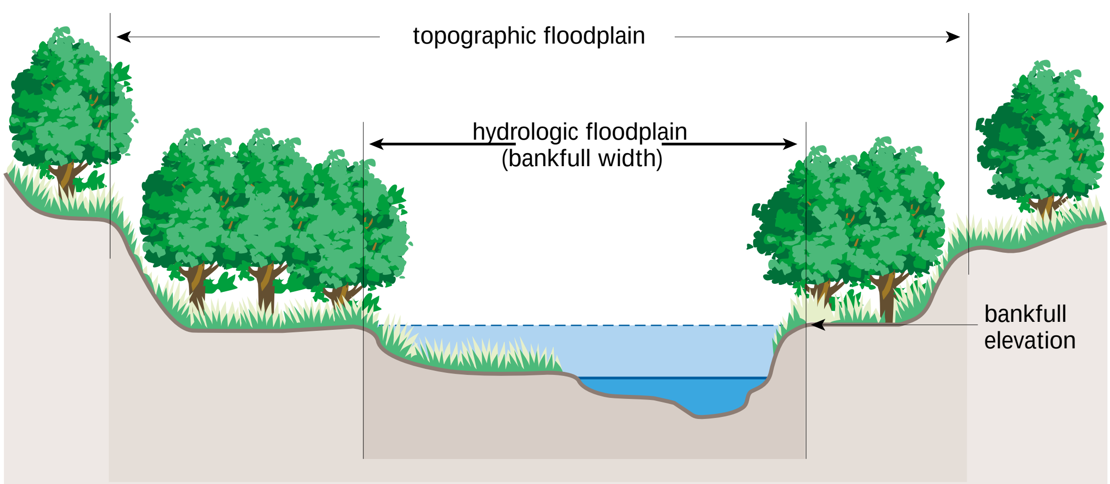


***Figure 1.20*: Hydrologic and topographic floodplains.** *The hydrologic floodplain is defined by bankfull elevation. The topographic floodplain includes the hydrologic floodplain and other lands up to a defined elevation.*

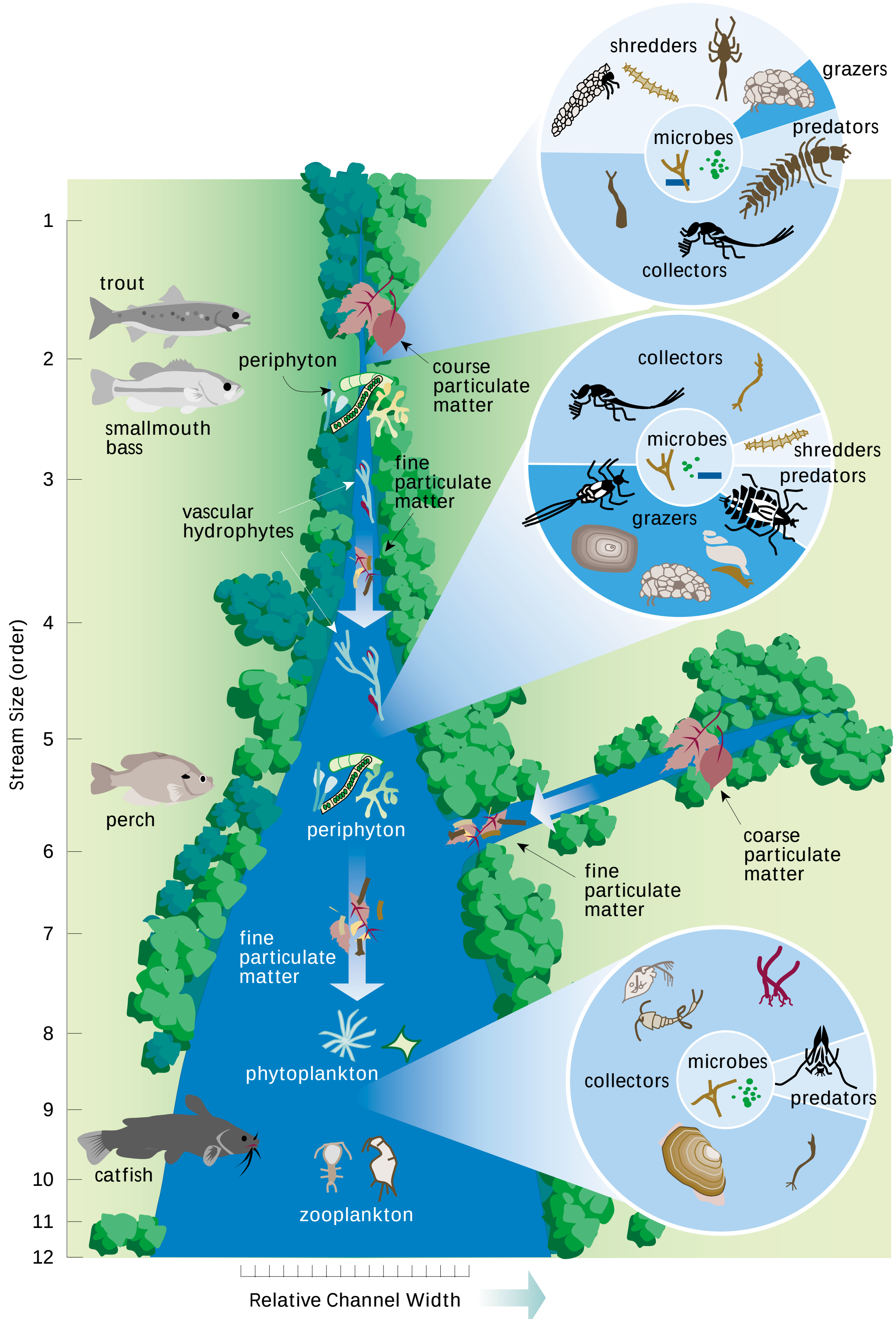


Figure 1.34: The River Continuum Concept. *The concept proposes a relationship between stream size and the progressive shift in structural and functional attributes.*
Source: Vannote et al. (1980). Published with the permission of NRC Research Press.

- *Measured load*, portion of the total sediment load that is obtained by the sampler in the sampling zone.
- *Unmeasured load*, portion of the total sediment load that passes beneath the sampler, both in suspension and on the bed. With typical suspended sediment samplers this is the lower 0.3 to 0.4 feet of the vertical.

The above terms can be combined in a number of ways to give the total sediment load in a stream (**Table 2.4**). However, it is important not to combine terms that are not compatible. For example, the suspended load and the bed material load are not complimentary terms because the suspended load may include a portion of the bed material load, depending on the energy available for transport. The total sediment load is correctly defined by the combination of the following terms:

Total Sediment Load =

Bed Material Load + Wash Load

or

Bed Load + Suspended Load

or

Measured Load + Unmeasured Load

Sediment transport rates can be computed using various equations or models. These are discussed in the *Stream Channel Restoration* section of Chapter 8.

Table 2.4: Sediment load terms.

<table>
<tr><td></td><td></td><td colspan="2">Classification System</td></tr>
<tr><td></td><td></td><td>Based on Mechanism of Transport</td><td>Based on Particle Size</td></tr>
<tr><td rowspan="3">Total sediment load</td><td>Wash load</td><td rowspan="2">Suspended load</td><td>Wash load</td></tr>
<tr><td>Suspended bed-material load</td><td rowspan="2">Bed-material load</td></tr>
<tr><td>Bed load</td><td>Bed load</td></tr>
</table>

Stream Power

One of the principal geomorphic tasks of a stream is to transport particles out of the watershed (**Figure 2.15**). In this manner, the stream functions as a transporting “machine;” and, as a machine, its rate of doing work can be calculated as the product of available power multiplied by efficiency.

Stream power can be calculated as:

$$\varphi = \gamma\, Q\, S$$

Where:

φ = Stream power (foot-lbs/second-foot)

γ = Specific weight of water (lbs/ft^3)

Q = Discharge (ft^3/second)

S = Slope (feet/feet)

Sediment transport rates are directly related to stream power; i.e., slope and discharge. Baseflow that follows the highly sinuous thalweg (the line that marks the deepest points along the stream channel) in a meandering stream generates little stream power; therefore, the stream’s ability to move sediment, *sediment-transport capacity,* is limited. At greater depths, the flow follows a straighter course, which increases slope, causing increased sediment transport rates. The stream builds its cross section to obtain depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel.

Runoff can vary from a watershed, either due to natural causes or land use practices. These variations may change the size distribution of sediments delivered to the stream from the watershed by preferentially moving particular particle sizes into the stream. It is not uncommon to find a layer of sand on top of a cobble layer. This often happens when accelerated erosion of sandy soils

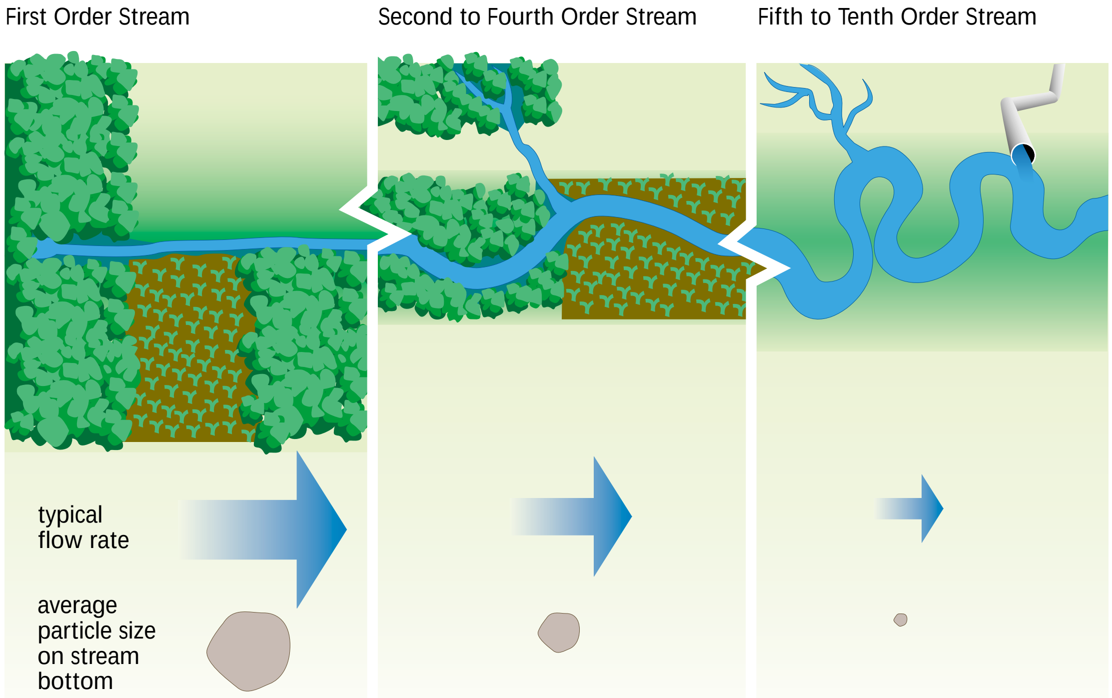


Figure 2.15: Particle transport. *A stream's total sediment load is the total of all sediment particles moving past a defined cross section over a specified time period. Transport rates vary according to the mechanism of transport.*

occurs in a watershed and the increased load of sand exceeds the transport capacity of the stream during events that move the sand into the channel.

Stream and Floodplain Stability

A question that normally arises when considering any stream restoration action is "Is it stable now and will it be stable after changes are made?" The answer may be likened to asking an opinion on a movie based on only a few frames from the reel. Although we often view streams based on a limited reference with respect to time, it is important that we consider the long-term changes and trends in channel cross section, longitudinal profile, and planform morphology to characterize channel stability.

Achieving channel stability requires that the average tractive stress maintains a stable streambed and streambanks. That is, the distribution of particle sizes in each section of the stream remains in equilibrium (i.e., new particles deposited are the same size and shape as particles displaced by tractive stress).

Yang (1971) adapted the basic theories described by Leopold to explain the longitudinal profile of rivers, the formation of stream networks, riffles, and pools, and river meandering. All these river characteristics and sediment transport are closely related. Yang (1971) developed the theory of average stream fall and the theory of least rate of energy expenditure, based on the entropy concept. These theories state that during the evolution toward an equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure per unit mass of flow along its course is a minimum.

Combining the four equations above yields additional predictive relationships for concurrent increases or decreases in streamflow and/or sediment discharge:

$$Q_w^+ Q_s^+ \sim b^+, d^{+/-}, L^+, S^{+/-}, P^-$$

$$Q_w^- Q_s^- \sim b^-, d^{+/-}, L^-, S^{+/-}, P^+$$

$$Q_w^+ Q_s^- \sim b^{+/-}, d^+, L^{+/-}, S^-, P^+$$

$$Q_w^- Q_s^+ \sim b^{+/-}, d^-, L^{+/-}, S^+, P^-$$

Channel Slope

Channel slope, a stream's longitudinal profile, is measured as the difference in elevation between two points in the stream divided by the stream length between the two points. Slope is one of the most critical pieces of design information required when channel modifications are considered. Channel slope directly impacts flow velocity, stream competence, and stream power. Since these attributes drive the geomorphic processes of erosion, sediment transport, and sediment deposition, channel slope becomes a controlling factor in channel shape and pattern.

(See Figs. 1-27 and 1-28)

Most longitudinal profiles of streams are concave upstream. As described previously in the discussion of dynamic equilibrium, streams adjust their profile and pattern to try to minimize the time rate of expenditure of potential energy, or stream power, present in flowing water. The concave upward shape of a stream's profile appears to be due to adjustments a river makes to help minimize stream power in a downstream direction. Yang (1983) applied the theory of minimum stream power to explain why most longitudinal streambed profiles are concave upward. In order to satisfy the theory of minimum stream power, which is a special case of the general theory of minimum energy dissipation rate (Yang and Song 1979), the following equation must be satisfied:

$$\frac{dP}{dx} = \gamma Q \frac{dS}{dx} + S \frac{dQ}{dx} = 0$$

Where:

P = QS = Stream power

x = Longitudinal distance

Q = Water discharge

S = Water surface or energy slope

γ = Specific weight of water

Stream power has been defined as the product of discharge and slope. Since stream discharge typically increases in a downstream direction, slope must decrease in order to minimize stream power. The decrease in slope in a downstream direction results in the concave-up longitudinal profile.

Sinuosity is not a profile feature, but it does affect stream slope. Sinuosity is the stream length between two points on a stream divided by the valley length between the two points. For example, if a stream is 2,200 feet long from point A to point B, and if a valley length distance between those two points is 1,000 feet, that stream has a sinuosity of 2.2. A stream can increase its length by increasing its sinuosity, resulting in a decrease in slope. This impact of sinuosity on channel slope must always be considered if channel reconstruction is part of a proposed restoration.

Pools and Riffles

The longitudinal profile is seldom constant, even over a short reach. Differences in geology, vegetation patterns, or human disturbances can result in flatter and steeper reaches within an overall profile. Riffles occur

Roughness plays an important r ole in streams. It helps determine the depth or stage of flow in a stream reach. As flow velocity slows in a stream reach due to roughness, the depth of flow has to increase to maintain the volume of flow that entered the upstream end of the reach (a concept known as flow continuity). Typical roughness along the boundaries of the stream includes the following:

- Sediment particles of different sizes.
- Bedforms.
- Bank irregularities.
- The type, amount, and distribution of living and dead vegetation.
- Other obstructions.

Roughness generally increases with increasing particle size. The shape and size of instream sediment deposits, or bedforms, also contribute to roughness.

Sand-bottom streams are good examples of how bedform roughness changes with discharge. At very low discharges, the bed of a sand stream may be dominated by ripple bedforms. As flow increases even more, sand dunes may begin to appear on the bed. Each of these bedforms increases the roughness of the stream bottom, which tends to slow velocity.

The depth of flow also increases due to increasing roughness. If discharge continues to increase, a point is reached when the flow velocity mobilizes the sand on the streambed and the entire bed converts again to a planar form. The depth of flow may actually decrease at this point due to the decreased roughness of the bed. If discharge increases further still, antidunes may form. These bedforms create enough friction to again cause the flow depth to increase. The depth of flow for a given discharge in sand-bed streams, therefore, depends on the bedforms present when that discharge occurs.

Vegetation can also contribute to roughness. In streams with boundaries consisting of cohesive soils, vegetation is usually the principal component of roughness. The type and distribution of vegetation in a stream corridor depends on hydrologic and geomorphic processes, but by creating roughness, vegetation can alter these processes and cause changes in a stream's form and pattern.

Meandering streams offer some resistance to flow relative to straight streams. Straight and meandering streams also have different distributions of flow velocity that are affected by the alignment of the stream, as shown in **Figure 2.17**. In straight reaches of a stream, the fastest flow occurs just below the surface near the center of the channel where flow resistance is lowest (see Figure 2.17 (a) Section G). In meanders, velocities are highest at the outside edge due to angular momentum (see Figure 2.17 (b) Section 3). The differences in flow velocity distribution in meandering streams result in both erosion and deposition at the meander bend. Erosion occurs at the outside of bends (cutbanks) from high velocity flows, while the slower velocities at the insides of bends cause deposition on the point bar (which also has been called the *slip-off slope*).

The angular momentum of flow through a meander bend increases the height or *super elevation* at the outside of the bend and sets up a secondary current of flow down the face of the cut bank and across the bottom of the pool toward the inside of the bend. This rotating flow is called *helical flow* and the direction of rotation is illustrated on the diagram on the following page by the arrows at the top and bottom of cross sections 3 and 4 in the figure.

minerals present in the watershed. For example, when an acid interacts with limestone, the following dissolution reaction occurs:

$$H^{+} + CaCO_3 = Ca^{2+} + HCO_3^{-}$$

This reaction consumes hydrogen ions, thus raising the pH of the water. Conversely, runoff may acidify when all alkalinity in the water is consumed by acids, a process often attributed to the input of strong mineral acids, such as sulfuric acid, from acid mine drainage, and weak organic acids, such as humic and fulvic acids, which are naturally produced in large quantities in some types of soils, such as those associated with coniferous forests, bogs, and wetlands. In some streams, pH levels can be increased by restoring degraded wetlands that intercept acid inputs, such as acid mine drainage, and help neutralize acidity by converting sulfates from sulfuric acid to insoluble nonacidic metal sulfides that remain trapped in wetland sediments.

pH, Alkalinity, and Acidity Along the Stream Corridor

Within a stream, similar reactions occur between acids in the water, atmospheric CO_2, alkalinity in the water column, and streambed material. An additional characteristic of pH in some poorly buffered waters is high daily variability in pH levels attributable to biological processes that affect the carbonate buffering system. In waters with large standing crops of aquatic plants, uptake of carbon dioxide by plants during photosynthesis removes carbonic acid from the water, which can increase pH by several units. Conversely, pH levels may fall by several units during the night when photosynthesis does not occur and plants give off carbon dioxide. Restoration techniques that decrease instream plant growth through increased shading or reduction in nutrient loads or that increase reaeration also tend to stabilize highly variable pH levels attributable to high rates of photosynthesis.

The pH within streams can have important consequences for toxic materials. High acidity or high alkalinity tend to convert insoluble metal sulfides to soluble forms and can increase the concentration of toxic metals. Conversely, high pH can promote ammonia toxicity. Ammonia is present in water in two forms, unionized (NH_3) and ionized (NH_4^{+}). Of these two forms of ammonia, un-ionized ammonia is relatively highly toxic to aquatic life, while ionized ammonia is relatively negligibly toxic. The proportion of un-ionized ammonia is determined by the pH and temperature of the water (Bowie et al. 1985)—as pH or temperature increases, the proportion of un-ionized ammonia and the toxicity also increase. For example, with a pH of 7 and a temperature of 68°F, only about 0.4 percent of the total ammonia is in the un-ionized form, while at a pH of 8.5 and a temperature of 78°F, 15 percent of the total ammonia is in the un-ionized form, representing 35 times greater potential toxicity to aquatic life.

Dissolved Oxygen

Dissolved oxygen (DO) is a basic requirement for a healthy aquatic ecosystem. Most fish and aquatic insects "breathe" oxygen dissolved in the water column. Some fish and aquatic organisms, such as carp and sludge worms, are adapted to low oxygen conditions, but most sport fish species, such as trout and salmon, suffer if DO concentrations fall below a concentration of 3 to 4 mg/L. Larvae and juvenile fish are more sensitive and require even higher concentrations of DO (USEPA 1997).

Many fish and other aquatic organisms can recover from short periods of low intra-riparian (longitudinal, elevational) gradient (Johnson and Lowe 1985). In the west, growth of riparian vegetation is increased by the “canyon effect” resulting when cool moist air spills downslope from higher elevations (**Figure 2.30**). This cooler air settles in canyons and creates a more moist microhabitat than occurs on the surrounding slopes. These canyons also serve as water courses. The combination of moist, cooler edaphic and atmospheric conditions is conducive to plant and animal species at lower than normal altitudes, often in disjunct populations or in regions where they would not otherwise occur (Lowe and Shannon 1954).

Plant Communities

The sensitivity of animal communities to vegetative characteristics is well recognized. Numerous animal species are associated with particular plant communities, many require particular developmental stages of those communities (e.g., old-growth), and some depend on particular habitat elements within those communities (e.g., snags). The structure of streamside plant communities also directly affects aquatic organisms by providing inputs of appropriate organic materials to the aquatic food web, by shading the water surface and providing cover along banks, and by influencing instream habitat structure through in-

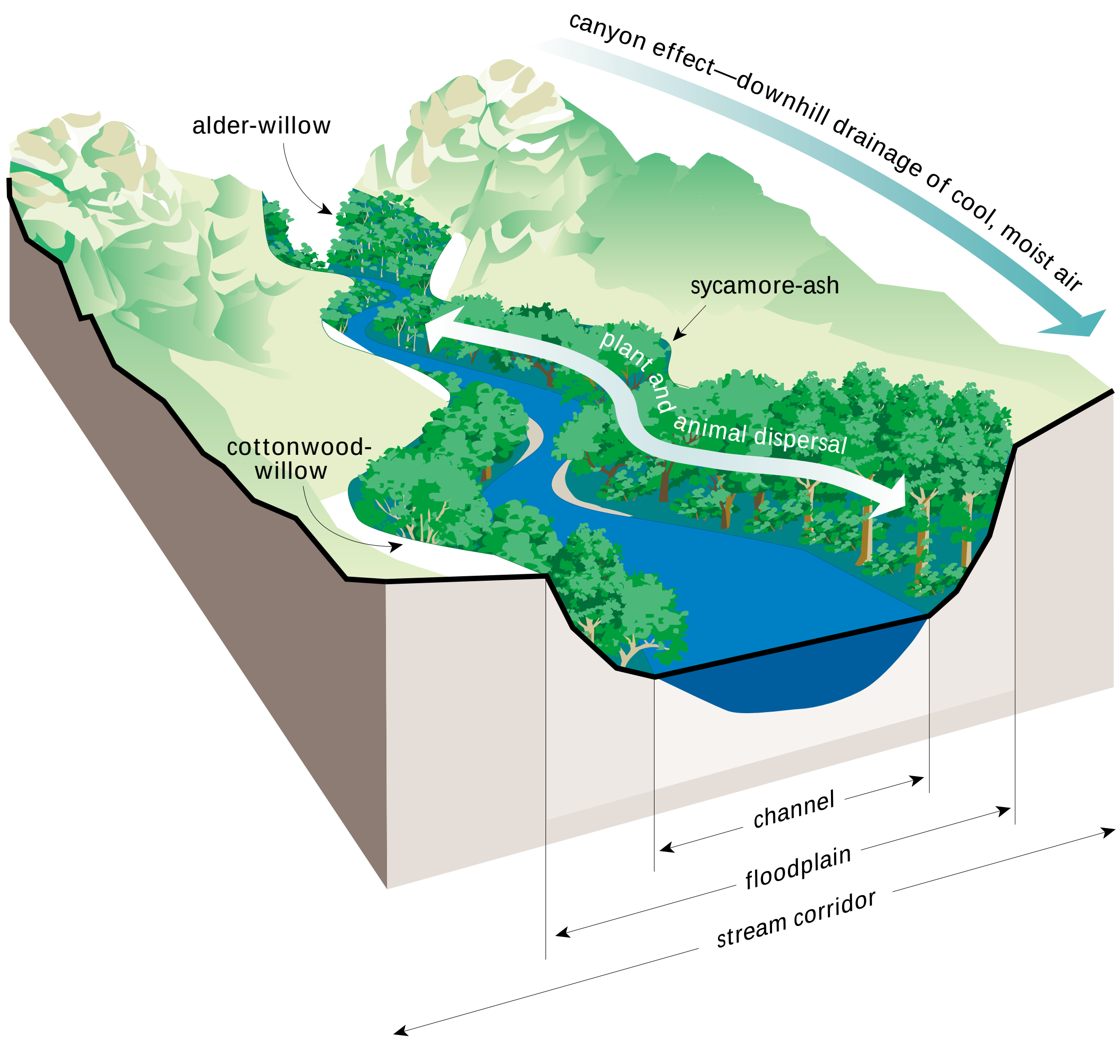


Figure 2.30: Canyon effect. *Cool moist air settles in canyons and creates microhabitat that occurs on surrounding slopes.*

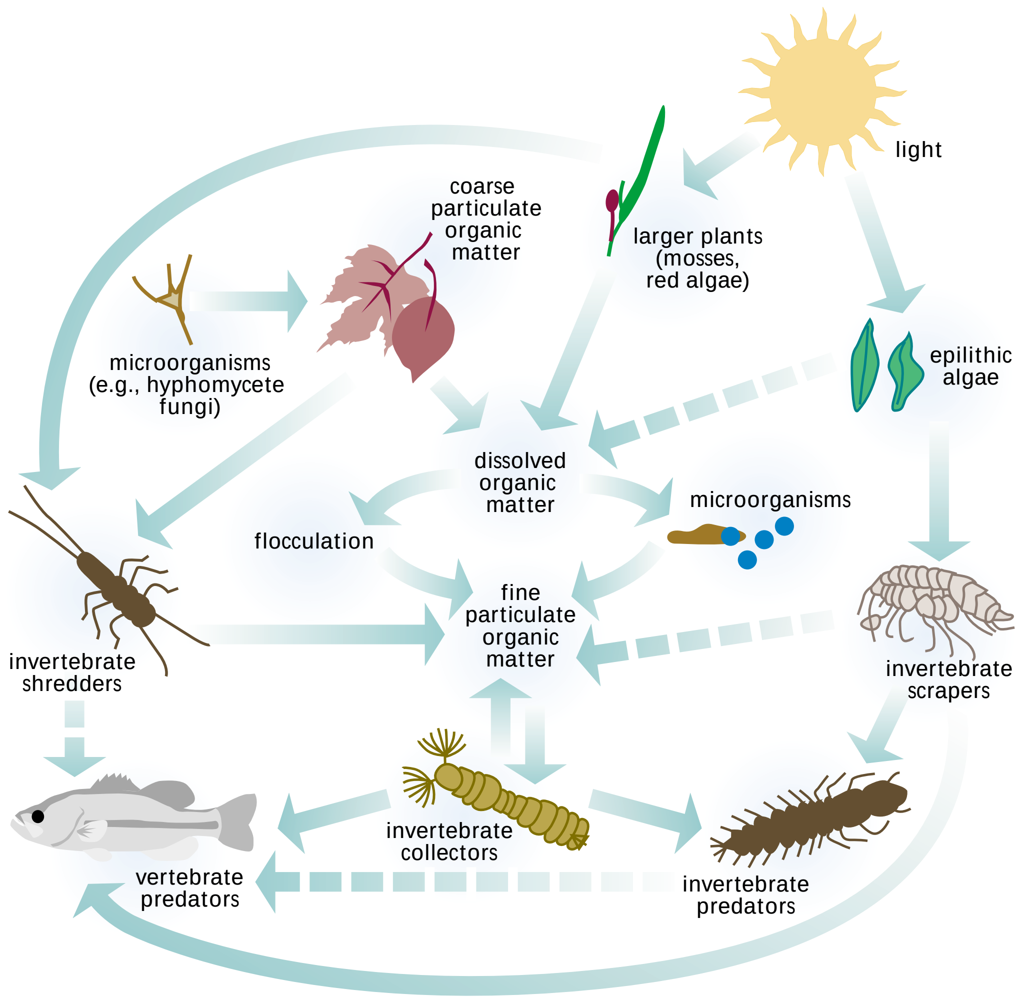


Figure 2.33: Stream biota. *Food relationships typically found n streams.*

Bourassa and Morin 1995). Furthermore, the larger species often play important roles in determining community composition of other components of the ecosystem. For example, herbivorous feeding activities of caddisfly larvae (Lamberti and Resh 1983), snails (Steinman et al. 1987), and crayfish (Lodge 1991) can have a significant effect on the abundance and taxonomic composition of algae and periphyton in streams. Likewise, macroinvertebrate predators, such as stoneflies, can influence the abundance of other species within the invertebrate community (Peckarsky 1985).

Table 2.12: Ranges of densities commonly observed for selected groups of stream biota.

Biotic Component	Density (Individuals/Square Mile)
Algae	$10^9 – 10^{10}$
Bacteria	$10^{12} – 10^{13}$
Protists	$10^8 – 10^9$
Microinvertebrates	$10^3 – 10^5$
Macroinvertebrates	$10^4 – 10^5$
Vertebrates	$10^0 – 10^2$

Collectively, microorganisms (fungi and bacteria) and benthic invertebrates facilitate the breakdown of organic material, such as leaf litter, that enters the stream from external sources. Some invertebrates (insect larvae and amphipods) act as shredders whose feeding activities break down larger organic leaf litter to smaller particles. Other invertebrates filter smaller organic material from the water (blackfly larvae, some mayfly nymphs, and some caddisfly larvae), scrape material off surfaces species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach (Benke et al. 1984, Smock et al. 1985, Huryn and Wallace 1987). This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams (Hackney et al. 1992).

Stream substrates can be viewed in the same functional capacity as soils in the terrestrial system; that is, stream substrates constitute the interface between water and the hyporheic subsurface of the aquatic system. The *hyporheic zone* is the area of substrate which lies below the substrate/water interface, and may range from a layer extending only inches beneath and laterally from the stream channel, to a very large subsurface environment. Alluvial floodplains of the Flathead River, Montana, have a hyporheic zone with significant surface water/ground water interaction which is 2 miles wide and 33 feet deep (Stanford and Ward 1988). Naiman et al. (1994) discussed the extent and connectivity of hyporheic zones around streams in the Pacific Northwest. They hypothesized that as one moves from low-order (small) streams to high-order (large) streams, the degree of hyporheic importance and continuity first increases and then decreases. In small streams, the hyporheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock. The hyporheic zones are generally not continuous. In mid-order channels with more extensive floodplains, the spatial connectivity of the hyporheic zone increases. In large order streams, the spatial extent of the hyporheic zone is usually greatest, but it tends to be highly discontinuous because of features associated with fluvial activities such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems (Naiman et al. 1994) (**Figure 2.35**).

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes (Minshall 1984). Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms (Odum 1971). As previously described, substrate size, heterogeneity, stability with respect to high and baseflow, and durability vary within streams, depending on particle size, density, and kinetic energy of flow. Inorganic substrates tend to be of larger size upstream than downstream and tend to be larger in riffles than in pools (Leopold et al. 1964). Likewise, the distribution and role of woody debris varies with stream size (Maser and Sedell 1994).

In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris that falls into the stream can increase the quantity and diversity of substrate and aquatic habitat or range (Bisson et al. 1987, Dolloff et al. 1994). Debris dams trap sediment behind them and often create scour holes immediately downstream. Eroded banks commonly occur at the boundaries of debris blockages.

Organic Material

Metabolic activity within a stream reach depends on autochthonous, allochthonous, and upstream sources of food and nutrients (Minshall et al. 1985). Autochthonous materials, such as algae and aquatic macrophytes, originate within the stream channel, whereas allochthonous materials such as wood, leaves, and dissolved organic carbon, originate outside the stream channel. Upstream materials may be of autochthonous or allochthonous origin and are transported by streamflow to downstream locations. Seasonal flooding provides allochthonous input of organic material to the stream channel and also can significantly increase the rate of decomposition of organic material.

The role of primary productivity of streams can vary depending on geographic location, stream size, and season (Odum 1957, Minshall 1978). The river continuum concept (Vannote et al. 1980) (see *The River Continuum Concept* in section 1.E in Chapter 1) hypothesizes that primary productivity is of minimal importance in shaded headwater streams but increases in significance as stream size increases and riparian vegetation no longer limits the entry of light to stream periphyton. Numerous researchers have demonstrated that primary productivity is of greater importance in certain ecosystems, including streams in grassland and desert ecosystems. Flora of streams can range from diatoms in high mountain streams to dense stands of macrophytes in low gradient streams of the Southeast.

As discussed in Section 2.C, loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as *eutrophication*. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems in waterbodies.

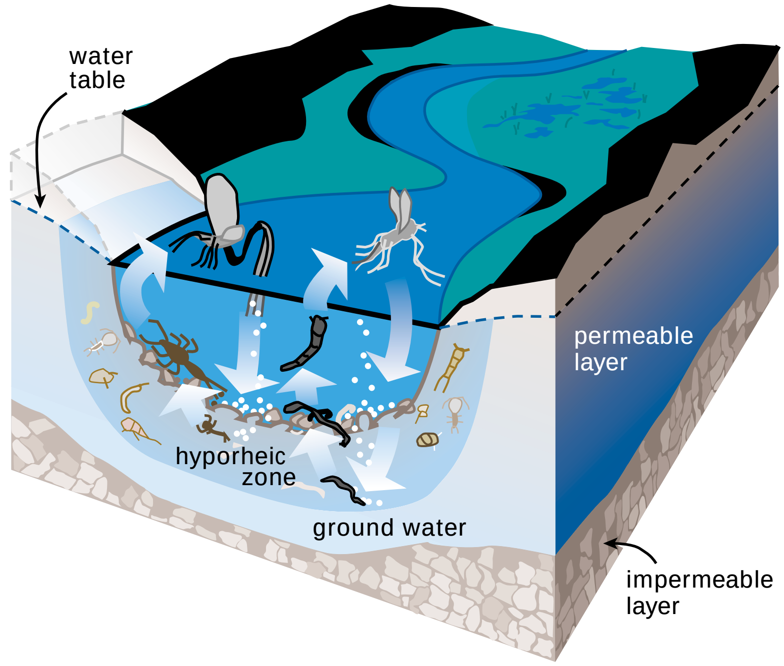


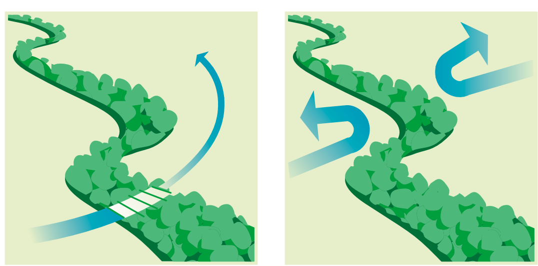
Figure 2.35: Hyporheic zone. *Summary of the different means of migration undergone by members of the stream benthic community.*

Eutrophication in lakes and reservoirs is indirectly measured as standing crops of phytoplankton biomass, usually represented by planktonic chlorophyll a concentration. However, phytoplankton biomass is usually not the dominant portion of plant biomass in smaller streams, due to periods of energetic flow and high substrate to volume ratios that favor the development of periphyton and macrophytes on the stream bottom. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures (**Figure 2.36**). Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

Local areas in the corridor are dependent on the flow of materials from one point to another. In the salmonid example, the local upland area adjacent to spawning grounds is dependent upon the nutrient transfer from the biomass of the fish into other terrestrial wildlife and off into the uplands. The local structure of the streambed and aquatic ecosystem are dependent upon the sediment and woody material from upstream and upslope to create a self-regulating and stable channel.

Stream corridor width is important where the upland is frequently a supplier of much of the natural load of sediment and biomass into the stream. A wide, contiguous corridor acts as a large conduit, allowing flow laterally and longitudinally along the corridor. Conduit functions are often more limited in narrow or fragmented corridors.

Filter and Barrier Functions



Stream corridors may serve as barriers that prevent movement or filters that allow selective penetration of energy, materials and organisms. In many ways, the entire stream corridor serves beneficially as a filter or barrier that reduces water pollution, minimizes sediment transport, and often provides a natural boundary to land uses, plant communities, and some less mobile wildlife species.

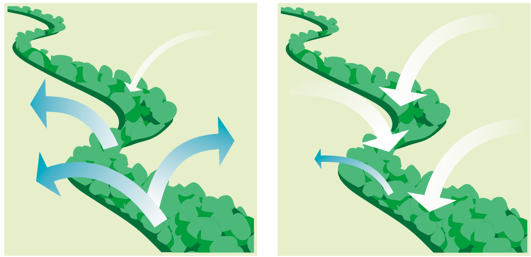
Materials, energy, and organisms which moved into and through the stream corridor may be filtered by structural attributes of the corridor. Attributes affecting barrier and filter functions include connectivity (gap frequency) and corridor width (**Figure 2.40**). Elements which are moving along a stream corridor edge may also be selectively filtered as they enter the stream corridor. In these circumstances it is the shape of the edge, whether it is straight or convoluted, which has the greatest effect on filtering functions. Still, it is most often movement perpendicular to the stream corridor which is most effectively filtered or halted.

Materials may be transported, filtered, or stopped altogether depending upon the width and connectedness of a stream corridor. Material movement across landscapes toward large river valleys may be intercepted and filtered by stream corridors. Attributes such as the structure of native plant communities can physically affect the amount of runoff entering a stream system through uptake, absorption, and interruption. Vegetation in the corridor can filter out much of the overland flow of nutrients, sediment, and water.

Siltation in larger streams can be reduced through a network of stream corridors functioning to filter excessive sediment. Stream corridors filter many of the upland materials from moving unimpeded across the landscape. Ground water and surface water flows are filtered by plant parts below and above ground. Chemical elements are intercepted by flora and fauna within stream corridors. A wider corridor provides more effective filtering, and a contiguous corridor functions as a filter along its entire length.

Breaks in a stream corridor can sometimes have the effect of funneling damaging processes into that area. For example, a gap in contiguous vegetation along a stream corridor can reduce the filtering function by focusing increased runoff into the area, leading to erosion,

Source and Sink Functions



Sources provide organisms, energy or materials to the surrounding landscape. Areas that function as sinks absorb organisms, energy, or materials from the surrounding landscape. Influent and effluent reaches, discussed in Section 1.B of Chapter 1, are classic examples of sources and sinks. The influent or "losing" reach is a source of water to the aquifer, and the effluent or "gaining" reach is a sink for ground water.

Stream corridors or features within them can act as a source or a sink of environmental materials. Some stream corridors act as both, depending on the time of year or location in the corridor. Streambanks most often act as a source, for example, of sediment to the stream. At times, however, they can function as sinks while flooding deposits new sediments there. At the landscape scale, corridors are connectors to various other patches of habitats in the landscape and as such they are sources and conduits of genetic material throughout the landscape.

Stream corridors can also act as a sink for storage of surface water, ground water, nutrients, energy, and sediment allowing for materials to be temporarily fixed in the corridor. Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter. Although these functions of source and sink are conceptually understood, they lack a suitable body of research and practical application guidelines.

Forman (1995) offers three source and sink functions resulting from floodplain vegetation:

- Decreased downstream flooding through floodwater moderation and/or uptake
- Containment of sediments and other materials during flood stage
- Source of soil organic matter and water-borne organic matter

Biotic and genetic source/sink relationships can be complex. Interior forest birds are vulnerable to nest parasitism by cowbirds when they try to nest in too small a forest patch. For these species, small forest patches can be considered sinks that reduce their population numbers and genetic diversity by causing failed reproduction. Large forest patches with sufficient interior habitat, in comparison, support successful reproduction and serve as sources of more individuals and new genetic combinations.

Dynamic Equilibrium

In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

The first two chapters of this document have emphasized that, although stream corridors display consistent patterns in their structure, processes, and functions, these patterns change naturally and constantly, even in the absence of human disturbance. Despite frequent change, streams and their corridors exhibit a dynamic form of stability. In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

The maintenance of dynamic equilibrium requires that a series of self-correcting mechanisms be active in the stream corridor ecosystem. These mechnumber and size of gravel bars are significantly different from what is evident in historical photos, for example, the difference might be an indication that either aggradation or erosion has been enhanced. Care is needed when using the channel to interpret possible changes in watershed conditions since similar channel symptoms can also be caused by changes in conditions within the stream corridor itself or by natural variation of the hydrograph.

Stream Corridor and Reach Factors Affecting Stream Corridor Conditions

In addition to watershed factors affecting stream corridor conditions, it is important to consider disturbances at the stream corridor and reach scales. In general, stream corridor structural attributes and functions are greatly affected by several important categories of activities if they occur within the corridor. Chapter 3 explores these in more detail; the following are some of the activities that commonly impact corridor structure and function.

- Activities that alter or remove streambank and riparian vegetation (e.g., grazing, agriculture, logging, and urbanization), resulting in changes in the stability of streambanks, runoff and transport of contaminants, water quality, or habitat characteristics of riparian zones (**Figure 4.14**).
- Activities that physically alter the morphology of channels, banks, and riparian zones, resulting in effects such as the displacement of aquatic and riparian habitat and the disruption of the flow of energy and materials (e.g., channelization, levee construction, gravel mining, and access trails).
- Instream modifications that alter channel shape and dimensions, flow hydraulics, sediment-transport characteristics, aquatic habitat, and water quality (e.g., dams and grade stabilization measures, bank riprap, logs, bridge piers, and habitat "enhancement" measures) (**Figure 4.15**). In the case of logs, it might be the loss of such structures rather than their addition that alters flow hydraulics and channel structure.

Figure 4.13: Water releases below a dam.
Altering the flow regime of river below Hoover Dam altered the stream condition.

Altered riparian vegetation and physical modification of channels and floodplains are primary causes of impaired stream corridor structure and functions because their effects are both profound and direct. Addressing the causes of these changes might offer the best, most feasible opportunities for restoring stream corridors. However, the altered vegetation and physical modifications also may create some of the most significant challenges for stream corridor restoration by constraining the number or type of possible solutions.

It is important to remember that there are no simple analytical methods available for analyzing relationships

FAST FORWARD

Preview Chapters 7 and 8, Analytical and Empirical Tools section.

sions to drainage area (**Figure 7.20**). Using these curves, the width and depth of the bankfull channel can be approximated once the drainage area of a watershed within one of these regions is known. Obviously, more curves such as these are needed for regions that experience different topographic, geologic, and hydrologic regimes; therefore, additional regional relationships should be developed for specific areas of interest. Several hydraulic geometry formulas are presented in **Table 7.5**.

Regional curves should be used only as indicators to help identify the channel geometry at a restoration initiative site

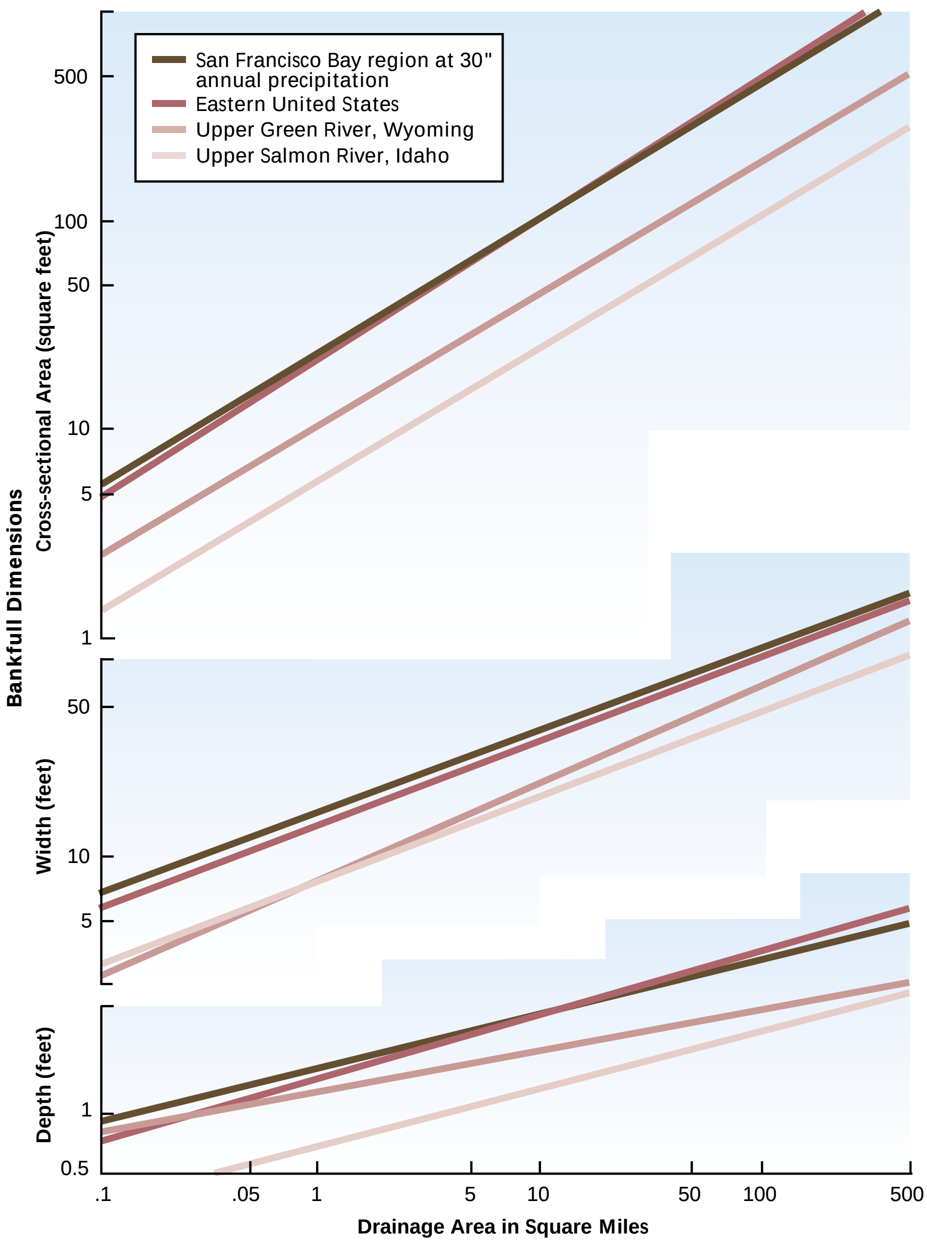


Figure 7.20: Regional curves for bankfull channel dimensions versus drainage area. *Curves showing channel dimensions relating to drainage area for a region of the country can be useful in determining departure from "normal" conditions. The use of such curves must be tempered with an understanding of the limitations of the specific data that produced the curves.*
Source: Dunne and Leopold 1978.

included to maximize amphibian richness. Examples of indirect methods to assess diversity include habitat models (Schroeder and Allen 1992, Adamus 1993) and cumulative impact assessment methods (Gosselink et al. 1990, Brooks et al. 1991).

Predicting diversity with a model is generally more rapid than directly measuring diversity. In addition, predictive methods provide a means to analyze alternative future conditions before implementing specific restoration plans. The reliability and accuracy of diversity models should be established before their use.

Classification Systems

Classification is an important component of many of the scientific disciplines relevant to stream corridors—hydrology, geomorphology, limnology, plant and animal ecology. **Table 7.9** lists some of the classification systems that might be useful in identifying and planning riverine restoration activities. It is not the intent of this section to exhaustively review all classification schemes or to present a single recommended classification system. Rather, we focus on some of the principal distinctions among classification systems and factors to consider in the use of classification systems for restoration planning, particularly in the use of a classification system as a measure of biological condition. It is likely that multiple systems will be useful in most actual riverine restoration programs.

The common goal of classification systems is to organize variation. Important dimensions in which riverine classification systems differ include the following:

- *Geographic domain*. The range of sites being classified varies from rivers of the world to local differences in the composition and characteristics of patches within one reach of a single river.
- *Variables considered*. Some classifications are restricted to abiotic vari-

Table 7.9: Selected riverine and riparian classification systems. *Classification systems are useful in characterizing biological conditions.*

Classification System	Subject	Geographic Domain	Citation
Riparian vegetation of Yampa, San Miguel/Dolores River Basins	Plant communities	Colorado	Kittel and Lederer (1993)
Riparian and scrubland communities of Arizona and New Mexico	Plant communities	Arizona and New Mexico	Szaro (1989)
Classification of Montana riparian and wetland sites	Plant communities	Montana	Hansen et al. (1995)
Integrated riparian evaluation guide	Hydrology, geomorphology, soils, vegetation	Intermountain	U.S. Forest Service (1992)
Streamflow cluster analysis	Hydrology with correlations to fish and invertebrates	National	Poff and Ward (1989)
River Continuum	Hydrology, stream order, water chemistry, aquatic communities	International, national	Vannote et al. (1980)
World-wide stream classification	Hydrology, water chemistry, substrate, vegetation	International	Pennak (1971)
Rosgen's river classification	Hydrology, geomorphology: stream and valley types	National	Rosgen (1996)
Hydrogeomorphic wetland classification	Hydrology, geomorphology, vegetation	National	Brinson (1993)
Recovery classes following channelization	Hydrology, geomorphology, vegetation	Tennessee	Simon and Hupp (1992)

posed by the two governing equations (e.g., sediment transport and flow resistance). Chang (1988) combined sediment transport and flow resistance formulas with flow continuity and minimization of stream power at each cross section and through a reach to generate a numerical model of flow and sediment transport. Special relationships for flow and transverse sediment transport in bends were also derived. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield d (bankfull depth) and w (bankfull width), given bankfull Q, S, and D_{50}. Separate sets of curves are provided for sand and gravel bed rivers. Regime-type formulas have been fit to the curves, as shown in **Table 8.3.** These relationships should be used with tractive stress analyses to develop converging data that increase the designer's confidence that the appropriate channel dimensions have been selected.

Subsequent work by Thorne et al. (1988) modified these formulas to account for effects of bank vegetation along gravel-bed rivers. The Thorne et al. (1988) formulas in Table 8.3 are based on the data presented by Hey and Thorne (1986) in Table 7.6.

Channels with Moving Beds and Known Sediment Concentration

White et al. (1982) present an analytical approach based on the Ackers and White sediment transport function, a companion flow resistance relationship, and maximization of sediment transport for a specified sediment concentration. Tables (White et al. 1981) are available to assist users in implementing this procedure. The tables contain entries for sediment sizes from 0.06 to 100 millimeters, discharges up to 35,000 cubic feet per second, and sedi-

Table 8.3: Equations for river width and depth.

Author	Year	Data	Domain	k_1	k_2	k_4	k_5
Chang	1988		Meandering or braided sand-bed rivers with:				
		Equiwidth point-bar streams and stable canals	$0.00238 < SD_{50}^{-0.5} Q^{-0.51}$ and $SD_{50}^{-0.5} Q^{-0.55} < 0.05$	$3.49k_1$*		$3.51k_4$*	0.47
		Straight braided streams	$0.05 < SD_{50}^{-0.5} Q^{-0.55}$ and $SD_{50}^{-0.5} Q^{-0.51} < 0.047$	Unknown and unusual			
		Braided point-bar and wide-bend point-bar streams; beyond upper limit lie steep, braided streams	$0.047 < SD_{50}^{-0.5} Q^{-0.51} <$ indefinite upper limit	$33.2k_1$**	0.93	$1.0k_4$**	0.45
Thorne et al.	1988	Same as for Thorne and Hey 1986	Gravel-bed rivers	$1.905 + k_1$***	0.47	$0.2077 + k_4$***	0.42
		Adjustments for bank vegetation[a]	Grassy banks with no trees or shrubs	$w = 1.46\ w_c - 0.8317$		$d = 0.8815\ d_c + 0.2106$	
			1-5% tree and shrub cover	$w = 1.306\ w_c - 8.7307$		$d = 0.5026\ d_c + 1.7553$	
			5-50% tree and shrub cover	$w = 1.161\ w_c - 16.8307$		$d = 0.5413\ d_c + 2.7159$	
			Greater than 50% tree and shrub cover, or incised into flood plain	$w = 0.9656\ w_c - 10.6102$		$d = 0.7648\ d_c + 1.4554$	

Chang equations for determining river width and depth. Coefficients for equations of the form $w = k_1 Q^{K_2}$; $d = K_4 Q^{K_5}$; where w is mean bankfull width (ft), Q is the bankfull or dominant discharge ($ft^3/_s$), d is mean bankfull depth (ft), D_{50} is median bed-material size (mm), and S is slope (ft/ft).

[a] w_c and d_c in these equations are calculated using exponents and coefficients from the row labeled "gravel-bed rivers".

$k_1* = (S\ D_{50}^{-0.5} - 0.00238Q^{-0.51})^{0.02}$.

$k_4* = \exp[-0.38\ (420.17S\ D_{50}^{-0.5}Q^{-0.51} - 1)^{0.4}]$.

$k_1** = (S\ D_{50}^{-0.5})^{0.84}$.

$k_4** = 0.015 - 0.025 \ln Q - 0.049 \ln (S\ D_{50}^{-0.5})$.

$k_1*** = 0.2490[\ln(0.0010647 D_{50}^{1.15}/SQ^{0.42})]^2$.

$k_4*** = 0.0418 \ln(0.0004419 D_{50}^{1.15}/SQ^{0.42})$.

tershed in northwest Mississippi should be stable with an average boundary shear stress at channel-forming (2-year) discharge of 0.4 to 0.9 lb/ft^2.

The value of the Shields constant also varies with bed material size distribution, particularly for paved or armored beds. Andrews (1983) derived a regression relationship that can be expressed as:

$$RS/[(S_s - 1)D_i] < 0.0834\ (D_i / D_{50})^{-0.872}$$

When the left side of the above expression equals the right, bed-sediment particles of size D_i are at the threshold of motion. The D_{50} value in the above expression is the median size of subsurface material. Therefore, if D_{50} = 30 mm, particles with a diameter of 100 mm will be entrained when the left side of the above equation exceeds 0.029. This equation is for self-formed rivers that have naturally sorted gravel and cobble bed material. The equation holds for values of D_i/D_{50} between 0.3 and 4.2. It should be noted that R and D_i on the left side of the above equation must be expressed in the same units.

Practical Guidance: Allowable Velocity and Shear Stress

Practical guidance for application of allowable velocity and shear stress approaches is provided by the Natural Resources Conservation Service (USDA-NRCS), formerly the U.S. Soil Conservation Service (SCS)(1977), and USACE (1994). See Figure 8.31.

Since form roughness due to sand dunes, vegetation, woody debris, and large geologic features in streams dissipates energy, allowable shear stress for bed stability may be higher than indicated by laboratory flume data or data from uniform channels. It is important to compute cross-sectional average velocities or shear stresses over a range of discharges and for seasonal changes in the erosion resistance of bank materials, rather than for a single design condition. Frequency and duration of discharges causing erosion are important factors in stability determination. In cobble- or boulder-bed streams, bed movement sometimes occurs only for discharges with return periods of several years.

Computing velocity or shear stress from discharge requires design cross sections, slope, and flow resistance data. If the design channel is not extremely uniform, typical or average conditions for rather short channel reaches should be considered. In channels with bends, variations in shear stress across the section can lead to scour and deposition even when average shear stress values are within allowable limits. The NRCS (formerly SCS) (1977) gives adjustment factors for channel curvature in graphical form that are based on very limited data (see Figure 8.31). Velocity distributions and stage-discharge relations for compound channels are complex (Williams and Julien 1989, Myers and Lyness 1994).

Allowable velocity or shear stress criteria should be applied to in-channel flow for a compound cross section with overbank flow, not cross-sectional average conditions (USACE 1994). Channel flow resistance predictors that allow for changing conditions with changing discharge and stage should be used rather than constant resistance values.

If the existing channel is stable, design channel slope, cross section, and roughness may be adjusted so that the current and proposed systems have matching curves of velocity versus discharge (USACE 1994). This approach, while based on allowable velocity concepts, releases the procedure from published empirical values collected in other rivers that might be intrinsically different from the one in question.

CASE STUDY Careless Creek, Montana

In the Big Snowy Mountains of central Montana, Careless Creek begins to flow through rangelands and fields until it reaches the Musselshell River. At the beginning of the century, the stream was lined with a riparian cover, primarily of willow. This stream corridor was home to a diversity of wildlife such as pheasant, beaver, and deer.

In the 1930s, a large reservoir was constructed to the west with two outlets, one connected to Careless Creek. These channels were meant to carry irrigation water to the area fields and on to the Musselshell River. Heavy flows during the summer months began to erode the banks (Figure 8.39a). In the following years, ranchers began clearing more and more brush for pasture, sometimes burning it out along a stream.

"My Dad carried farmer's matches in his pocket. There was a worn spot on his pants where he would strike a match on his thigh," said Jessie Zeier, who was raised on a ranch near Careless Creek, recalling how his father often cleared brush.

This accelerated streambank erosion, and use of water for irrigation increased. Conflicts arose over the quality and quantity of water, as riparian vegetation continued to be cleared. Groups then began working together to resolve problems. A Technical Advisory Sterring Committee was developed to help the planning effort. Many organizations took part, including the Upper and Lower Musselshell Conservation Districts; Natural Resources Conservation Service; Montana Department of Natural Resources and Conservation; Montana Department of Fish; Wildlife and Parks; Deadman's Basin Water Users Association; U.S. Bureau of Reclamation; Central Montana RC&D; City of Roundup; Roundup Sportsmen; county commissioners; and local landowners.

As part of the planning effort, a geographic information system resource inventory was begun in 1993. The inventory revealed about 50 percent of the banks along the 18 miles of Careless Creek were eroding. The inventory helped to locate the areas causing the most problems. Priority was given to headquarters, corrals, and croplands, where stabilization of approximately 5,000 feet of streambank has taken place, funded by EPA monies.

Passive efforts have also begun to stabilize the banks. Irrigation flows in Careless Creek have been decreased for the past 5 years, enabling some areas, such as the one pictured, to begin to self-heal (Figure 8.39b). Vegetation has been given a chance to root as erosion has begun to stabilize. Other practices, such as fencing, are being implemented, and future treatments are planned to provide a long-term solution.

Figure 8.39: Careless Creek. *(a) Eroded streambank (May 1995) and (b) streambank in recovery (December 1997).*

(a)

(b)

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