8

Restoration Design

8.A Valley Form, Connectivity, and Dimension

- *How do you incorporate all the spatial dimensions of the landscape into stream corridor restoration design?*
- *What criteria can be applied to facilitate good design decisions for stream corridor restoration?*

8.B Soil Properties

- *How do soil properties impact the design of restoration activities?*
- *What are the major functions of soils in the stream corridor?*
- *How are important soil characteristics, such as soil microfauna and soil salinity, accounted for in the design process?*

8.C Vegetative Communities

- *What is the role of vegetative communities in stream corridor restoration?*
- *What functions do vegetative communities fulfill in a stream corridor?*
- *What are some considerations in designing plant community restoration to ensure that all landscape functions are addressed?*
- *What is soil bioengineering and what is its role in stream corridor restoration?*

8.D Riparian / Terrestrial Habitat Recovery

- *What are some specific tools and techniques that can be used to ensure recovery of riparian and terrestrial habitat recovery?*

8.E Stream Channel Restoration

- *When is stream channel reconstruction an appropriate restoration option?*
- *How do you delineate the stream reach to be reconstructed?*
- *How is a stream channel designed and reconstructed?*
- *What are important factors to consider in the design of channel reconstruction (e.g., alignment and average slope, channel dimensions)?*
- *Are there computer models that can assist with the design of channel reconstruction?*

8.F Streambank Restoration Design

- *When should streambank stabilization be included in a restoration?*
- *How do you determine the performance criteria for streambank treatment, including the methods and materials to be used?*
- *What are some streambank stabilization techniques that can be considered for use?*

8.G In-Stream Habitat Recovery

- *What are the principal factors controlling the quality of instream habitat?*
- *How do you determine if an instream habitat structure is needed, and what type of structure is most appropriate?*
- *What procedures can be used to restore instream habitat?*
- *What are some examples of instream habitat structures?*
- *What are some important questions to address before designing, selecting or installing an instream habitat structure?*

8.H Land Use Scenarios

- *What role does land use play in stream corridor degradation and restoration?*
- *What design approaches can be used to address the impacts of various land uses (e.g., dams, agriculture, forestry, grazing, mining, recreation, urbanization)?*
- *What are some disturbances that are often associated with specific land uses?*
- *What restoration measures can be used to mitigate the impacts of various land uses?*
- *What are the potential effects of the restoration measures?*

8

Restoration Design

Design can be defined as the intentional shaping of matter, energy, and process to meet an expressed need. Planning and design connect natural processes and cultural needs through exchanges of materials, flows of energy, and choices of land use and management. One test of a successful stream corridor design is how well the restored system sustains itself over time while accommodating identified needs.

*To achieve success, those carrying out restoration design and implementation in variable-land-use settings must understand the stream corridor, watershed, and landscape as a complex of working ecosystems that influence and are influenced by neighboring ecosystems (***Figure 8.1***). The probability of achieving long-term, self-sustaining functions across this spatial complex increases with*

Figure 8.1: Stream running through a wet meadow. *Restoration design must consider site-specific conditions as an integral part of larger systems.*

“Leave It Alone / Let It Heal Itself”

There is a renewed emphasis on recovering damaged rivers (Barinaga 1996). Along with this concern, however, people should be reminded periodically that they serve as stewards of watersheds, not just tinkerers with stream sites. Streams in pristine condition, for example, should not be artificially “improved” by active rehabilitation methods.

At the other end of the spectrum, and particularly where degradation is caused by off-stream activities, the best solution to a river management problem might be to remove the problem source and “let it heal itself.” Unfortunately, in severely degraded streams this process can take a long time. Therefore the “leave it alone” concept can be the most difficult approach for people to accept (Gordon et al. 1992).

an understanding of these relationships, a common language for expressing them, and subsequent response. Designing to achieve stream- or corridor-specific solutions might not resolve problems or recognize opportunities in the landscape.

Stream corridor restoration design is still largely in an experimental stage. It is known however, that restoration design must consider site-specific or local conditions to be successful. That is, the design criteria, standards, and specifications should be for the specific project in a specific physical, climatic, and geographic location. These initiatives, however, can and should work with, rather than against, the larger systems of which they are an integral part.

This approach produces multiple benefits, including:

- A healthy, sustainable pattern of land uses across the landscape.
- Improved natural resource quality and quantity.
- Restored and protected stream corridors and associated ecosystems.
- A diversity of native plants and animals.
- A gene pool that promotes hardiness, disease resistance, and adaptability.
- A sense of stewardship for private landowners and the public.
- Improved management measures that avoid narrowly focused and fragmented land treatment.

Building on information presented in Parts I and II, this chapter contains design guidance and techniques to address changes caused by major disturbances and to restore stream corridor structure and function to a desired level. It begins with larger-scale influences that design may have on stream corridor ecosystems, offers design guidance primarily at the stream corridor and stream scales, and concludes with land use scenarios.

The chapter is divided into seven sections.

Section 8.A: Valley Form, Connectivity, and Dimension

This section focuses on restoring structural characteristics that prevail at the stream corridor and landscape scales.

Section 8.B: Soil Properties

The restoration of soil properties that are critical to stream corridor structure and functions are addressed in this section.

Section 8.C: Plant Communities

Restoring vegetative communities is a highly visible and integral component of a functioning stream corridor.

Section 8.D: Habitat Measures

This section presents design guidance for some habitat measures. They are often integral parts of stream corridor structure and functions.

Section 8.E: Stream Channel Restoration

Restoring stream channel structure and functions is often a fundamental step in restoring stream corridors.

Section 8.F: Streambank Restoration

This section focuses on design guidelines and related techniques for streambank stabilization. These measures can help reduce surface runoff and sediment transport to the stream.

Section 8.G: Instream Habitat Recovery

Restoring instream habitat structure and functions is often a key component of stream corridor restoration.

Section 8.H: Land Use Scenarios

This final section offers broad design concepts in the context of major land use scenarios.

8.A Valley Form, Connectivity, and Dimension

Valley form, connectivity, and dimension are variable structural characteristics that determine the interrelationship of functions at multiple scales. Valley intersections (nodes) with tributary stream corridors, slope of valley sides, and floodplain gradient are characteristics of valley form that influence many functions (**Figure 8.2**).


(a)


(b)

Figure 8.2: Stream corridors. *(a) Stream valley side slopes and (b) floodplain gradients influence stream corridor function.*

The broad concept of connectivity, as opposed to fragmentation, involves linkages of habitats, species, communities, and ecological processes across multiple scales (Noss 1991). Dimension encompasses width, linearity, and edge effect, which are critical for movement of species, materials, and energy within the stream corridor and to or from ecosystems in the surrounding landscape. Design should therefore address these large-scale characteristics and their effect on functions.

Valley Form

In some cases, entire stream valleys have changed to the point of obscuring geomorphic boundaries, making stream corridor restoration difficult. Volcanoes, earthquakes, and landslides are examples of natural disturbances that cause changes in valley form. Encroachment and filling of floodplains are among the human-induced disturbances that modify valley shape.

Stream Corridor Connectivity and Dimension

Connectivity and dimensions of the stream corridor present a set of design-related decisions to be made. How wide should the corridor be? How long should the corridor be? What if there are gaps in the corridor? These structural characteristics have a significant impact on corridor functions. The width, length, and connectivity of existing or potential stream corridor vegetation, for example, are critical to habitat functions within the corridor and adjacent ecosystems.

Generally, the widest and most contiguous stream corridor which achieves habitat, conduit, filter, and other functions (see Chapter 2) should be an ecologically derived goal of restoration. Thresholds for each function are likely found at different corridor widths. The appropriate width varies according to soil type, with steep slopes requiring a wider corridor for filter functions. A conservative indicator of effective corridor width is whether a stream corridor can significantly prevent chemical contaminants contained in runoff from reaching the stream (Forman 1995).

As discussed in Chapter 1, the corridor should extend across the stream, its banks, the floodplain, and the valley slopes. It should also include a portion of upland for the entire stream length to maintain functional integrity (Forman and Godron 1986).

A contiguous, wide stream corridor might not be achievable, however, particularly where competing land uses prevail. In these cases, a ladder pattern of natural habitat crossing the floodplain and connecting the upland segments might facilitate sediment trapping during floods and provide hydraulic storage and organic matter for the stream system (Dramstad et al. 1996).

Figure 8.3 presents an example of these connections. The open areas within the ladder pattern are representative of areas that are unavailable for restoration because of competing land uses.

Innovative management practices that serve the functions of the corridor beyond land ownership boundaries can often be prescribed where land owners are supportive of restoration. Altering land cover, reducing chemical inputs, carefully timed mowing, and other management practices can reduce disturbance in the corridor.

Practical considerations may restrict restoration to a zone of predefined width adjacent to the stream. Although often unavoidable, such restrictions tend to result in underrepresentation of older, off-channel environments that support vegetation different from that in stream-front communities. Restricting restoration to a narrow part of the stream corridor usually does not restore the full horizontal diversity of broad floodplains, nor does it fully accommodate functions that occur during flood events, such as use of the floodplain by aquatic species (Wharton et al. 1982).

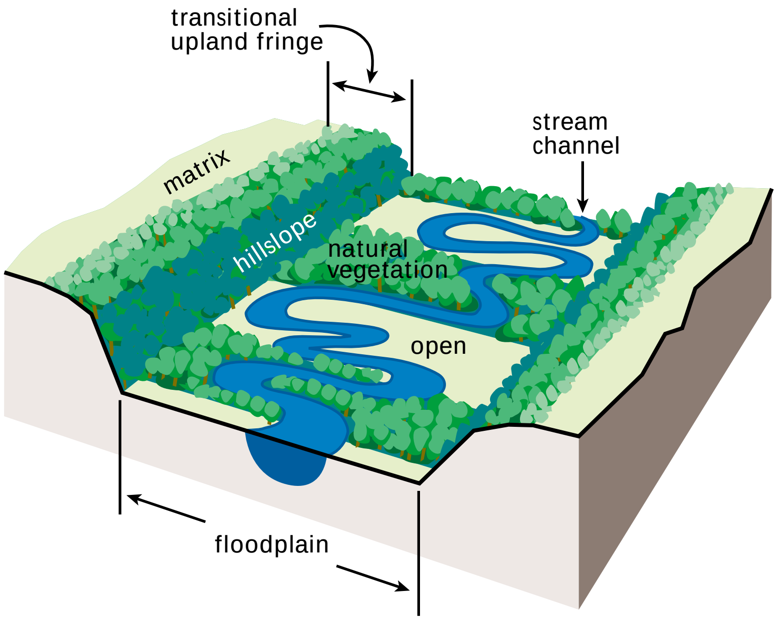


Figure 8.3: Connections across a stream corridor. *A ladder pattern of natural habitat can restore structure and functions where competing land uses prevail.*

Adapted from Ecology of Greenways: Design and Function of Linear Conservation Areas. Edited by Smith and Hellmund. © University of Minnesota Press 1993.

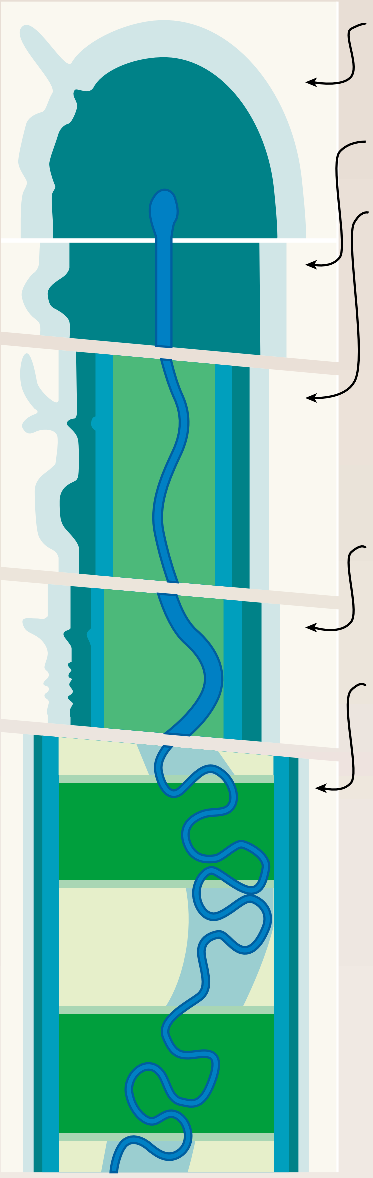
In floodplains where extensive subsurface hydrologic connections exist, limiting restoration to streamside buffer zones is not recommended since significant amounts of energy, nutrient transformation, and invertebrate activities can occur at great distances from the stream channel outside the buffer areas (Sedell et al. 1990). Similarly, failure to anticipate channel migration or periodic beaver activity might result in a corridor that does not accommodate

Corridor Width Variables

*The minimum width of stream corridors based on ecological criteria (**Figure 8.4**). Five basic situations in a river system are identified, progressing from seepage to river. The key variables determining minimum corridor width are listed under each.*

Figure 8.4: Factors for determining minimum corridor widths. *Stream corridor functions are directly influenced by corridor width.*

Source: Forman 1995. Reprinted with permission of Cambridge University Press.



Seepage

1. Sponge effect for hydrologic flows, mimimizing downstream flooding
2. Control of dissolved-substance inputs from matrix

1st Order Stream

1. Same as for seepage

2nd to 4th Order Stream with Closed Canopy

1. Conduit for upland interior species; both sides of stream so species readily crossing floodplain have alternate routes
2. Control of dissolved-substance inputs from matrix
3. Conduit for streambank and floodplain species, where beaver activities maintain water across the floodplain and alter hillslope vegetation
4. Minimize hillslope erosion
5. Sponge effect for hydrologic flows, minimizing downstream flooding
6. Friction effect, minimizing downstream sedimentation
7. Protect high habitat diversity and species richness of floodplain

2nd to 4th Order Stream with Open Canopy

1. Same as for 2nd to ca. 4th order stream, closed canopy
2. Provide interior habitat for species conduit, as migrating open stream intersects hillslopes causing them to be open habitat

5th to 10th Order River

1. Conduit for upland interior species, on both sides of river so species that rarely can cross the floodplain have a route on each side
2. Provide interior habitat for species conduit, as migrating open river intersects hillslopes causing them to be open habitat
3. Minimize hillslope erosion
4. Shade and logs provide fish habitat where river is adjacent to hillslope
5. Source of soil organic matter, an important base of the river food chain
6. Shade and logs provide fish habitat wherever river is as it migrates across the floodplain
7. Genetic benefit to upland species that can use habitat continuity to infrequently cross floodplain
8. Sponge effect for hydrologic flows, minimizing downstream flooding
9. Friction effect minimizing downstream sedimentation
10. Protect high habitat diversity and species richness of floodplain
11. Conduit for semiaquatic and other organisms dependent on river channel resources

- ⬜ matrix
- 🟦 edge portion of corridor in upland
- 🟦 interior portion of corridor in upland
- 🟦 hillslope
- 🟩 floodplain
- 🟦 meander band
- 🟩 interior of patch of natural floodplain vegetation
- 🟩 edge of patch of natural floodplain vegetation
- ⬜ other ecologically-compatible land use

fundamental dynamic processes (Malanson 1993).

As previously discussed, restoration of an ecologically effective stream corridor requires consideration of uplands adjacent to the channel and floodplain. Hillslopes might be a source area for water maintaining floodplain wetlands, a sediment source for channels on bedrock, and the principal source of organic debris in high-gradient streams.

Despite these considerations, stream corridors are often wrongly viewed as consisting of only the channel and an adjacent vegetative buffer. The width of the buffer is determined by specific objectives such as control of agricultural runoff or habitat requirements of particular animal species. This narrow definition obviously does not fully accommodate the extent of the functions of a stream corridor; but where the corridor is limited by immovable resource uses, it often becomes a part of a restoration strategy.

Cognitive Approach: The Reference Stream Corridor

Ideal stream corridor widths, as previously defined, are not always achievable in the restoration design. A local reference stream corridor might provide dimensions for designing the restoration.

Examination of landscape patterns is beneficial in identifying a reference stream corridor. The reference should provide information about gap width, landform, species requirements, vegetative structure, and boundary characteristics of the stream corridor (**Figure 8.5**).

Restoration objectives determine the desired levels of functions specified by the restoration design. If a nearby stream corridor in a similar landscape setting and with similar land use variables provides these functions adequately, it can be used to indicate the connectivity and width attributes that should be part of the design.

Figure 8.5: A maple in a New Mexico floodplain. *A rare occurrence of a remnant population may reflect desired conditions in a reference stream corridor.*

Analytical Approach: Functional Requirements of a Target Species

The restoration plan objectives can be used to determine dimensions for the stream corridor restoration. If, for example, a particular species requires that the corridor offer interior habitat, the corridor width is sized to provide the necessary habitat. The requirements of the most sensitive species typically are used for optimum corridor dimensions. When these dimensions extend beyond the land base available for restoration, management of adjacent land uses becomes a tool for making the corridor effectively wider than the project parameters.

Optimum corridor dimensions can be achieved through collaboration with individuals and organizations who have management authority over adjacent lands. Dimensions include width of edge effect associated with boundaries of the corridor and pattern variations within the corridor, maximum acceptable width of gaps within the corridor, and maximum number of gaps per unit length of corridor.

Designing for Drainage and Topography

The stream corridor is dependent on interactions with the stream to sustain its character and functions (see Chapter 2). Therefore, to the extent feasible, the restoration process should include blockage of artificial drainage systems, removal or setback of artificial levees, and restoration of natural patterns of floodplain topography, unless these actions conflict with other social or environmental objectives (e.g., flooding or habitat).

Restoration of microrelief is particularly important where natural flooding has been reduced or curtailed because a topographically complex floodplain supports a mosaic of plant communities and ecosystem functions as a result of differential ponding of rainfall and interception of ground water. Microrelief restoration can be accomplished by selective excavation of historic features within the floodplain such as natural wetlands, levees, oxbows, and abandoned channels. Aerial photography and remotely sensed data, as well as observations in reference corridors, provide an indication of the distribution and dimensions of typical floodplain microrelief features.

8.B Soil Properties

Stream corridor functions depend not only on the connectivity and dimensions of the stream corridor, but also on its soils and associated vegetation. The variable nature of soils across and along stream corridors results in diverse plant communities (**Figure 8.6**). When designing stream corridor restoration measures, it is important to carefully analyze the soils and their related potentials and limitations to support diverse native plant and animal communities, as well as for restoration involving channel reconstruction.

Where native floodplain soils remain in place, county soil surveys should be used to determine basic site conditions and fertility and to verify that the proposed plant species to be restored are appropriate. Most sites with fine-textured alluvium will not require supplemental fertilization, or fertilizers might be required only for initial establishment. In these cases excessive fertil-

Figure 8.6: Distinct vegetation zones along a mountain stream. *Variable soils result in diverse plant communities.*

ization could encourage competing weed species or exotics. Soil should always be tested before making any fertilizer design recommendations.

County soil surveys can provide basic information such as engineering limitations or suitabilities. Site-specific soil samples should, however, be collected and tested when the restoration involves alternatives that include stream reconstruction.

The connections and feedback loops between runoff and the structure and functions of streams are described in Chapter 2. The functions of soil and the connection between soil quality, runoff, and water quality are also established in that chapter. These connections need to be identified and considered in any stream corridor restoration plan and design. For all land uses, emphasis needs to be placed on implementing conservation land treatment that promotes soil quality and the ability of the soils to carry out four major functions:

- Regulating and partitioning the flow of water (a conduit and filter function).
- Storing and cycling nutrients and other chemicals (a sink and filter function).
- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials (a filter, sink, and barrier function).
- Supporting biological activity in the landscape (a source and habitat function).

References such as *Field Office Technical Guide* (USDA-NRCS) contain guidance on the planning and selection of conservation practices and are available at most county offices.

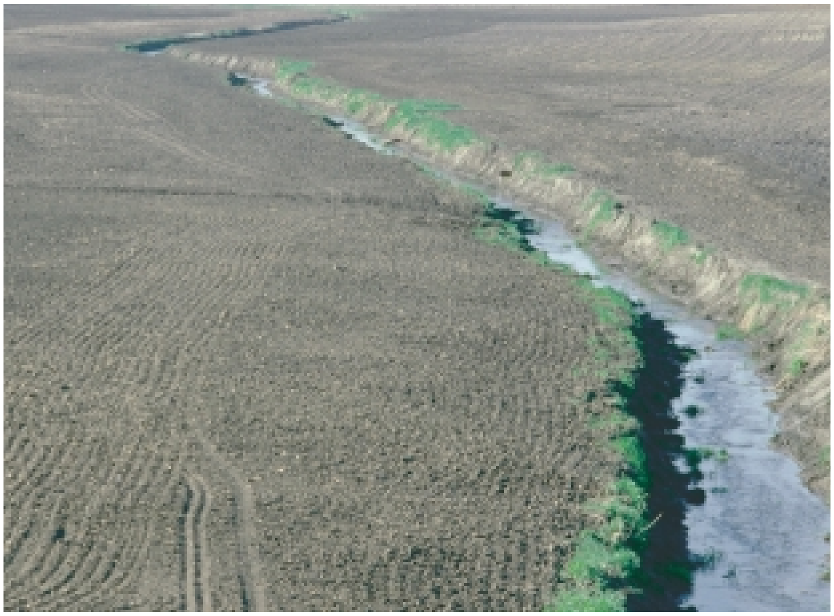


Figure 8.7: Compaction of streamside soil. *Compact soils may require deep plowing, ripping, or vegetative practices to break up the impermeable layer.*

Compaction

Soils that have been in row crops or have undergone heavy equipment traffic (such as that associated with construction) can develop a relatively impermeable compacted layer (plow pan or hard pan) that restricts water movement and root penetration (**Figure 8.7**). Such soils might require deep plowing, ripping, or vegetative practices to break up the pan, although even these are sometimes ineffective. Deep plowing is usually expensive and, at least in the East, should be used only if the planting of a species that is able to penetrate the pan layer is not a viable option.

Soil Microfauna

On new or disturbed substrates, or on row-cropped sites, essential soil microorganisms (particularly mycorrhizal fungi) might not exist. These are most effectively replaced by using rooted plant material that is inoculated or naturally infected with appropriate fungi. Stockpiling and reincorporating local topsoils into the substrate prior to planting is also effective (Allen 1995). Particular care should be taken to avoid disturbing large trees or stumps since the soils around and under them are likely source areas for reestablishment of a wide variety of microorganisms. Inoculation can be useful in restoring some soil mycorrhizal fungi for particular species when naturally infected plant stock is unavailable.

Soil Salinity

Soil salinity is another important consideration in restoration because salt accumulation in the soil can restrict plant growth and the establishment of riparian species. High soil salinity is not common in healthy riparian ecosystems where annual spring floods remove excess salts. Soil salinity can also be altered by leaching salts through the soil profile with irrigation (Anderson et al. 1984). Because of agricultural drainage and altered flows due to dam construction, salt accumulation often contributes to riparian plant community declines.

Soil sampling throughout a restoration site may be necessary since salinity can vary across a floodplain, even on sites of less than 20 acres. If salinity is a problem, one must select plant materials adapted to a saline soil environment.

8.C Plant Communities

Vegetation is a fundamental controlling factor in stream corridor function. Habitat, conduit, filter/barrier, source, and sink functions are all critically tied to the vegetative biomass amount, quality, and condition (**Figure 8.8**). Restoration designs should protect existing native vegetation and restore vegetative structure to result in a contiguous and connected stream corridor.

Restoration goals can be general (e.g., returning an area to a reference condition) or specific (e.g., restoring habitats for particular species of interest such as the least Bell's vireo, Vireo *bellii* [Baird and Rieger 1988], or yellow-billed cuckoo, *Coccyzus americana* [Anderson and Laymon 1988]).

Numerous shrubs and trees have been evaluated as restoration candidates, including willows (Svejcar et al. 1992, Hoag 1992, Conroy and Svejcar 1991, Anderson et al. 1978); alder, serviceberry, oceanspray, and vine maple (Flessner et al. 1992); cottonwood and poplar (Hoag 1992); Sitka and thinleaf alder (Java and Everett 1992); palo verde and honey mesquite (Anderson et al. 1978); and many others. Selection of vegetative species may be based on the desire to provide habitat for a particular species of interest. The current trend in restoration, however, is to apply a multispecies or ecosystem approach.

Figure 8.8: Stream corridor vegetation. *Vegetation is a fundamental controlling factor in the functioning of stream corridors.*

Riparian Buffer Strips

Managers of riparian systems have long recognized the importance of buffer strips, for the following reasons (USACE 1991):

- Provide shade that reduces water temperature.
- Cause deposition of (i.e., filter) sediments and other contaminants.
- Reduce nutrient loads of streams.
- Stabilize streambanks with vegetation.
- Reduce erosion caused by uncontrolled runoff.
- Provide riparian wildlife habitat.
- Protect fish habitat.
- Maintain aquatic food webs.
- Provide a visually appealing greenbelt.
- Provide recreational opportunities.

Although the value of buffer strips is well recognized, criteria for their sizing are variable. In urban stream corridors a wide forest buffer is an essential component of any protection strategy. Its primary value is to provide physical protection for the stream channel from future disturbance or encroachment. A network of buffers acts as the right-of-way for a stream and functions as an integral part of the stream ecosystem.

Often economic and legal considerations have taken precedence over ecological factors. For Vermont, USACE (1991) suggests that narrow strips (100 ft. wide) may be adequate to provide many of the functions listed above. For breeding bird populations on Iowa streams, Stauffer and Best (1980) found that minimum strip widths varied from 40 ft. for cardinals to 700 ft. for scarlet tanagers, American redstarts, and rufous-sided towhees.

In urban settings buffer sizing criteria may be based on existing site controls as well as economic, legal, and ecological factors. Practical performance criteria for sizing and managing urban buffers are presented in the box Designing Urban Stream Buffers. Clearly, no single recommendation would be suitable for all cases.

Because floodplain/riparian habitats are often small in area when compared to surrounding uplands, meeting the minimum area needs of a species, guild, or community is especially important. Minimum area is the amount of habitat required to support the expected or appropriate use and can vary greatly across species and seasons. For example, Skagen (USGS, Biological Resources Division, Ft. Collins, Colorado; unpubl. data) found that, contrary to what might be considered conventional wisdom, extensive stream corridors in southeastern Arizona were not more important to migrating birds than isolated patches or oases of habitat. In fact, oases that were <2.5 miles long and <30 ft. in width had more species and higher numbers of nonbreeding migrants than did corridors. Skagen found that the use of oases, as well as corridors, is consistent with the observed patterns of long distance migrants, where migration occurs along broad fronts rather than north-south corridors. Because small and/or isolated patches of habitat can be so important to migrants, riparian restoration efforts should not overlook the important opportunities they afford.

Existing Vegetation

Existing native vegetation should be retained to the extent feasible, as should woody debris and stumps (**Figure 8.9**). In addition to providing habitat and erosion and sediment control, these features provide seed sources and harbor a

Designing Urban Stream Buffers

The ability of an urban stream buffer to realize its many benefits depends to a large degree on how well it is planned, designed, and maintained. Ten practical performance criteria are offered to govern how a buffer is to be sized, managed, and crossed. The key criteria include:

Criteria 1: Minimum total buffer width.

Most local buffer criteria require that development be set back a fixed and uniform distance from the stream channel. Nationally, urban stream buffers range from 20 to 200 ft. in width from each side of the stream according to a survey of 36 local buffer programs, with a median of 100 ft. (Schueler 1995). In general, a minimum base width of at least 100 feet is recommended to provide adequate stream protection.

Criteria 2: Three-zone buffer system.

*Effective urban stream buffers have three lateral zones—stream side, middle core, and outer zone. Each zone performs a different function, and has a different width, vegetative target and management scheme. The **stream side zone** protects the physical and ecological integrity of the stream ecosystem. The vegetative target is mature riparian forest that can provide shade, leaf litter, woody debris, and erosion protection to the stream. The **middle zone** extends from the outward boundary of the stream side zone, and varies in width, depending on stream order, the extent of the 100-yr floodplain, adjacent steep slopes, and protected wetland areas. Its key functions are to provide further distance between upland development and the stream. The vegetative target for this zone is also mature forest, but some clearing may be allowed for storm water management, access, and recreational uses.*

*The **outer zone** is the buffer's "buffer," an additional 25-ft. setback from the outward edge of the middle zone to the nearest permanent structure. In most instances, it is a residential backyard. The vegetative target for the outer zone is usually turf or lawn, although the property owner is encouraged to plant trees and shrubs, and thus increase the total width of the buffer. Very few uses are restricted in this zone. Indeed, gardening, compost piles, yard wastes, and other common residential activities often will occur in the outer zone.*

Criteria 3: Predevelopment vegetative target.

The ultimate vegetative target for urban stream buffers should be specified as the predevelopment riparian plant community—usually mature forest. Notable exceptions include prairie streams of the Midwest, or arroyos of the arid West, that may have a grass or shrub cover in the riparian zone. In general, the vegetative target should be based on the natural vegetative community present in the floodplain, as determined from reference riparian zones. Turfgrass is allowed for the outer zone of the buffer.

Criteria 4: Buffer expansion and contraction.

Many communities require that the minimum width of the buffer be expanded under certain conditions. Specifically, the average width of the middle zone can be expanded to include:

- *the full extent of the 100-yr floodplain;*
- *all undevelopable steep slopes (greater than 25%);*
- *steep slopes (5 to 25% slope, at four additional ft. of slope per one percent increment of slope above 5%); or*
- *any adjacent delineated wetlands or critical habitats.*

Criteria 5: Buffer delineation.

Three key decisions must be made when delineating the boundaries of a buffer. At what mapping scale will streams be defined? Where does the stream begin and the buffer end? And from what point should the inner edge of the buffer be measured? Clear and workable delineation criteria should be developed.

Criteria 6: Buffer crossings.

Major objectives for stream buffers are to maintain an unbroken corridor of riparian forest and to allow for upstream and downstream fish passage in the stream network. From a practical standpoint, however, it is not always possible to try to meet these goals everywhere along the stream buffer network. Some provision must be made for linear forms of development that must cross the stream or the buffer, such as roads, bridges, fairways, underground utilities, enclosed storm drains or outfall channels.

Criteria 7: Storm water runoff.

Buffers can be an important component of the storm water treatment system at a development site. They cannot, however, treat all the storm water runoff generated within a watershed (generally, a buffer system can only treat runoff from less than 10% of the contributing watershed to the stream). Therefore, some kind of structural BMP must be installed to treat the quantity and quality of storm water runoff from the remaining 90% of the watershed.

Criteria 8: Buffers during plan review and construction.

The limits and uses of the stream buffer systems should be well defined during each stage of the development process—from initial plan review, through construction.

Criteria 9: Buffer education and enforcement.

The future integrity of a buffer system requires a strong education and enforcement program. Thus, it is important to make the buffer "visible" to the community, and to encourage greater buffer awareness and stewardship among adjacent residents. Several simple steps can be taken to accomplish this.

- Mark the buffer boundaries with permanent signs that describe allowable uses
- Educate buffer owners about the benefits and uses of the buffer with pamphlets, stream walks, and meetings with homeowners associations
- Ensure that new owners are fully informed about buffer limits/uses when property is sold or transferred
- Engage residents in a buffer stewardship program that includes reforestation and backyard "bufferscaping" programs
- Conduct annual buffer walks to check on encroachment

Criteria 10: Buffer flexibility.

In most regions of the country, a hundred-foot buffer will take about 5% of the total land area in any given watershed out of use or production. While this constitutes a relatively modest land reserve at the watershed scale, it can be a significant hardship for a landowner whose property is adjacent to a stream. Many communities are legitimately concerned that stream buffer requirements could represent an uncompensated "taking" of private property. These concerns can be eliminated if a community incorporates several simple measures to ensure fairness and flexibility when administering its buffer program. As a general rule, the intent of the buffer program is to modify the location of development in relation to the stream but not its overall intensity. Some flexible measures in the buffer ordinance include:

- Maintaining buffers in private ownership
- Buffer averaging
- Density compensation
- Variances
- Conservation easements

Figure 8.9: Remnant vegetation and woody debris along a stream. *Attempts should be made to preserve existing vegetation within the stream corridor.*

variety of microorganisms, as described above. Old fencerows, vegetated stumps and rock piles in fields, and isolated shade trees in pastures should be retained through restoration design, as long as the dominant plant species are native or are unlikely to be competitors in a matrix of native vegetation (e.g., fruit trees).

Nonnative vegetation can prevent establishment of desirable native species or become an unwanted permanent component of stream corridor vegetation. For example, kudzu will kill vegetation. Generally, forest species planted on agricultural land will eventually shade out pasture grasses and weeds, although some initial control (disking, mowing, burning) might be required to ensure tree establishment.

Plant Community Restoration

An objective of stream corridor restoration work might be to restore natural patterns of plant community distribution within the stream corridor. Numerous publications describe general distribution patterns for various geomorphic settings and flow conditions (e.g., Brinson et al. 1981, Wharton et al. 1982), and county soil surveys generally describe native vegetation for particular soils. More detailed and site-specific plant community descriptions may be available from state Natural Heritage programs, chapters of The Nature Conservancy, or other natural resources agencies and organizations.

Examination of the reference stream corridor, however, is often the best way to develop information on plant community composition and distribution. Once reference plant communities are defined, design can begin to detail the measures required to restore those communities (**Figure 8.10**). Rarely is it feasible or desirable to attempt to plant the full complement of appropriate species on a particular site. Rather, the more typical approach is to plant the dominant species or those species unlikely to colonize the site readily. For example, in the complex bottom-

Figure 8.10: A thriving and diverse plant community within a stream corridor. *Examination of reference plant communities is often the best way to develop information on the composition and distribution of plant communities at the restoration site.*

land hardwood forests of the Southeast, the usual focus is on planting oaks. Oaks are heavy-seeded, are often shade-intolerant, and may not be able to readily invade large areas for generations unless they are introduced in the initial planting plan, particularly if flooding has been reduced or curtailed. It is assumed that lighter-seeded and shade-tolerant species will invade the site at rates sufficient to ensure that the resulting forest is adequately diverse. This process can be accelerated by planting corridors of fast-growing species (e.g., cottonwoods) across the restoration area to promote seed dispersal.

In areas typically dominated by cottonwoods and willows, the emphasis might be to emulate natural patterns of colonization by planting groves of particular species rather than mixed stands, and by staggering the planting program over a period of years to ensure structural variation. Where conifers tend to eventually succeed riparian hardwoods, some restoration designs may include scattered conifer plantings among blocks of pioneer species, to accelerate the transition to a conifer-dominated system.

Large-scale restoration work sometimes includes planting of understory species, particularly if they are required to meet specific objectives such as providing essential components of endangered species habitat. However, it is often difficult to establish understory species, which are typically not tolerant to full sun, if the restoration area is open. Where particular understory species are unlikely to establish themselves for many years, they can be introduced in adjacent forested sites, or planted after the initial tree plantings have matured sufficiently to create appropriate understory conditions. This may also be an appropriate approach for introducing certain overstory species that might not survive planting in full sun (**Figure 8.11**).

Figure 8.11: Restoration of understory plant species. *Understory species can be introduced at the restoration site after the initial tree plantings have matured sufficiently.*

The concept of focusing restoration actions on a limited group of overstory species to the exclusion of understory and other overstory species has been criticized. The rationale for favoring species such as oaks has been to ensure that restored riparian and floodplain areas do not become dominated by opportunistic species, and that wildlife functions and timber values associated with certain species will be present as soon as possible. It has been documented that heavy-seeded species such as oaks may be slow to invade a site unless planted (see Tennessee Valley Authority Floodplain Reforestation Projects—50 Years Later), but differential colonization rates probably exclude a variety of other species as well. Certainly, it would be desirable to introduce as wide a variety of appropriate species as possible; however, costs and the difficulties of doing supplemental plantings over a period of years might preclude this approach in most instances.

Low Water Availability

In areas where water levels are low, artificial plantings will not survive if their roots cannot reach the zone of saturation. Low water availability was associated with low survival rates in more than 80 percent of unsuccessful revegetation work examined in Arizona (Briggs 1992). Planting long poles (20 ft.) of Fremont cottonwood (Populus fremontii) and Gooding willow in augered holes has been successful where the ground water is more than 10 ft. below the surface (Swenson and Mullins 1985). In combination with an irrigation system, many planted trees are able to reach ground water 10 ft. below the surface when irrigated for two seasons after planting (Carothers et al. 1990). Sites closest to ground water, such as secondary channels, depressions, and low sites where water collects, are the best candidates for planting, although low-elevation sites are more prone to flooding and flood damage to the plantings. Additionally, the roots of many riparian species may become dormant or begin to die if inundated for extended periods of time (Burrows and Carr 1969).

Plant species should be distributed within a restoration site with close attention to microsite conditions. In addition, if stream meandering behavior or scouring flows have been curtailed, special effort is required to maintain communities that normally depend on such behavior for natural establishment. These may include oxbow and swale communities (bald cypress, shrub wetlands, emergent wetlands), as well as communities characteristic of newly deposited soils (cottonwoods, willows, alders, silver maple, etc.). It is important to recognize that planting vegetation on sites where regeneration mechanisms no longer operate is a temporary measure, and long-term management and periodic replanting is required to maintain those functions of the ecosystem.

In the past, stream corridor planting programs often included nonnative species selected for their rapid growth rates, soil binding characteristics, ability to produce abundant fruits for wildlife, or other perceived advantages over native species. These actions sometimes have unintended consequences and often prove to be extremely detrimental (Olson and Knopf 1986). As a result, many local, county, state, and federal agencies discourage or prohibit planting of nonnative species within wetlands or streamside buffers. Stream corridor restoration designs should emphasize native plant species from local sources. It may be feasible in some cases to focus restoration actions on encouraging the success of local seedfall to ensure that locally adapted populations of stream corridor vegetation are maintained on the site (Friedmann et al. 1995).

Plant establishment techniques vary greatly depending on site conditions and species characteristics. In arid regions, the emphasis has been on using poles or cuttings of species that sprout readily, and planting them to depths that will ensure contact with moist soil during the dry season (**Figure 8.12**). Where water tables have declined precipitously, deep auguring and temporary irrigation are used to establish cuttings and rooted or container-grown plants. In environments where precipitation or ground water is adequate to sustain planted vegetation, prolonged irrigation is less common, and bare-root or container-grown plants are often used, particularly for species that do not sprout reliably from cuttings. On large floodplains of the South and East, direct seeding of acorns and planting of dormant bare-root material have been highly successful. Other options, such as transplanting of salvaged plants, have been tried with varying degrees of success. Local experience should be sought to determine the most reliable and efficient plant establishment approaches for particular areas and species, and to determine what problems to expect.

It is important to protect plantings from livestock, beaver, deer, small mammals, and insects during the establishment period. Mortality of vegetation from deer browsing is common and can be prevented by using tree shelters to protect seedlings.

Figure 8.12: Revegetation with the use of deeply planted live cuttings. *In arid regions, poles or cuttings of species that sprout readily are often planted to depths that assure contact with moist soil.*

Horizontal Diversity

Stream corridor vegetation, as viewed from the air, would appear as a mosaic of diverse plant communities that runs from the upland on one side of the stream corridor, down the valley slope, across the floodplain, and up the opposite slope to the upland. With such broad dimensional range, there is a large potential for variation in vegetation. Some of the variation is a result of hydrology and stream dynamics, which will be discussed later in this chapter. Three important structural characteristics of horizontal diversity of vegetation are connectivity, gaps, and boundaries.

Stream corridor restoration designs should emphasize native plant species from local sources.

Connectivity and Gaps

As discussed earlier, connectivity is an important evaluation parameter of stream corridor functions, facilitating the processes of habitat, conduit, and filter/barrier. Stream corridor restoration design should maximize connections between ecosystem functions. Habitat and conduit functions can be enhanced by linking critical ecosystems to stream corridors through design that emphasizes orientation and proximity. Designers should consider functional connections to existing or potential features such as vacant or abandoned land, rare habitat, wetlands or meadows, diverse or unique vegetative communities, springs, ecologically innovative residential areas, movement corridors for flora and fauna, or associated stream systems. This allows for movement of materials and energy, thus increasing conduit functions and effectively increasing habitat through geographic proximity.

Generally, a long, wide stream corridor with contiguous vegetative cover is favored, though gaps are commonplace. The most fragile ecological functions determine the acceptable number and size of gaps. Wide gaps can be barriers to mi-

Tennessee Valley Authority Floodplain Reforestation Projects—50 Years Later

*The oldest known large-scale restoration of forested wetlands in the United States was undertaken by the Tennessee Valley Authority in conjunction with reservoir construction projects in the South during the 1940s. Roads and railways were relocated outside the influence of maximum pool elevations, but where they were placed on embankments, TVA was concerned that they would be subject to wave erosion during periods of extreme high water. To reduce that possibility, agricultural fields between the reservoir and the embankments were planted with trees (***Figure 8.13***). At Kentucky Reservoir in Kentucky and Tennessee, approximately 1,000 acres were planted, mostly on hydric soils adjacent to tributaries of the Tennessee River. Detailed records were kept regarding the species planted and survival rates. Some of these stands were recently located and studied to evaluate the effectiveness of the original reforestation effort, and to determine the extent to which the planted forests have come to resemble natural stands in the area.*

Because the purpose of the plantings was erosion control, little thought was given to recreating natural patterns of plant community composition and structure. Trees were evenly spaced in rows, and planted species were apparently chosen for maximum flood tolerance. As a result, the studied stands had an initial composition dominated by bald cypress, green ash, red maple, and similarly

Figure 8.13: Kentucky Reservoir watershed, 1943.
Planting abandoned farmland with trees.

water-tolerant species, but they did not originally contain many of the other common bottomland forest species, such as oaks.

Shear et al. (in press) compared the plant communities of the planted stands with forests on similar sites that had been established by natural invasion of abandoned fields. They also looked at older stands that had never been converted to agriculture. The younger planted and natural stands were similar to the older stands with regard to understory composition, and measures of stand density and biomass were consistent with patterns typical for the age of the stands. Overstory composition of the planted stands was very different from that of the others, reflecting the original plantings. However, both the planted sites and the fields that had been naturally invaded had few individuals of heavy-seeded species (oaks and hickories), which made up 37 percent of the basal area of the older stands.

Figure 8.14: Kentucky Reservoir watershed in 1991. *Thriving bottomland hardwood forest.*

*Oaks are an important component of southern bottomlands and are regarded as particularly important to wildlife. In most modern restoration plantings, oaks are favored on the assumption that they will not quickly invade agricultural fields. The stands at Kentucky Reservoir demonstrate that planted bottomland forests can develop structural and understory conditions that resemble those of natural stands within 50 years (**Figure 8.14**). Stands that were established by natural invasion of agricultural fields had similar characteristics. The major compositional deficiency in both of the younger stands was the lack of heavy-seeded species. The results of this study appear to support the practice of favoring heavy-seeded species in bottomland forest restoration initiatives.*

gration of smaller terrestrial fauna and indigenous plant species. Aquatic fauna may also be limited by the frequency or dimension of gaps. The width and frequency of gaps should therefore be designed in response to planned stream corridor functions. Bridges have been designed to allow migration of animals, along with physical and chemical connections of river and wetland flow. In Florida, for example, underpasses are constructed beneath roadways to serve as conduits for species movement (Smith and Hellmund 1993). The Netherlands has experimented with extensive species overpasses and underpasses to benefit particular species (**Figure 8.15**). Although not typically equal to the magnitude of an undisturbed stream corridor lacking gaps, these measures allow for modest functions as habitat and conduit.

Restored plant communities should be designed to exhibit structural diversity and canopy closure similar to that of the reference stream corridor.

The filtering capacity of stream corridors is affected by connectivity and gaps. For example, nutrient and water discharge flowing overland in sheet flow tends to concentrate and form rills. These rills in turn often form gullies. Gaps in vegetation offer no opportunity to slow overland flow or allow for infiltration. Where reference dimensions are similar and transferable, restored plant communities should be designed to exhibit structural diversity and canopy closure similar to that of the reference stream corridor. The reference stream corridor can provide information regarding plant species and their frequency and distribution. Design should aim to maintain the filtering capacity of the stream corridor by minimizing gaps in the corridor's width and length.

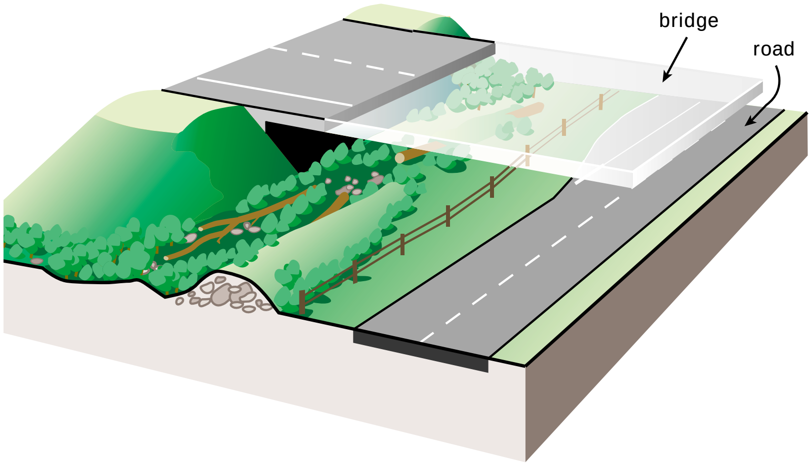


***Figure 8.15*: Underpass design.** *Underpasses should be designed to accommodate both vehicular traffic and movement of small fauna.*

Buffer configuration and composition have also received attention since they influence wildlife habitat quality, including suitability as migration corridors for various species and suitability for nesting habitat. Reestablishment of linkages among elements of the landscape can be critically important for many species (Noss 1983, Harris 1984). However, as noted previously, fundamental considerations include whether a particular vegetation type has ever existed as a contiguous corridor in an area, and whether the predisturbance corridor was narrow or part of an expansive floodplain forest system. Establishment of inappropriate and narrow corridors can have a net detrimental influence at local and regional scales (Knopf et al. 1988). Local wildlife management priorities should be evaluated in developing buffer width criteria that address these issues.

Boundaries

The structure of the edge vegetation between a stream corridor and the adjacent landscape affects the habitat, conduit, and filter functions. A transition between two ecosystems in an undisturbed environment typically occurs across a broad area.

Boundaries between stream corridors and adjacent landscapes may be straight or curvilinear. A straight boundary allows relatively unimpeded movement along the edge, thereby decreasing species interaction between the two ecosystems. Conversely, a curvilinear boundary with lobes of the corridor and adjoining areas reaching into one another encourages movement across boundaries, resulting in increased interaction. The shape of the boundary can be designed to integrate or discourage these interactions, thus affecting the habitat, conduit, and filter functions.

Species interaction may or may not be desirable depending on the project goals. The boundary of the restoration initiative can, for example, be designed to capture seeds or to integrate animals, including those carrying seeds. In some cases, however, this interaction is dictated by the functional requirements of the adjacent ecosystem (equipment tolerances within an agricultural field, for instance).

Vertical Diversity

Heterogeneity within the stream corridor is an important design consideration. The plants that make up the stream corridor, their form (herbs, shrubs, small trees, large trees), and their diversity affect function, especially at the reach and site scales. Stratification of vegetation affects wind, shading, avian diversity, and plant growth (Forman 1995). Typically, vegetation at the edge of the stream corridor is very different from the vegetation that occurs within the interior of the corridor. The topography, aspect, soil, and hydrology of the corridor provide several naturally diverse layers and types of vegetation.

The difference between edge and interior vegetative structure are important design considerations (**Figure 8.16**). An edge that gradually changes from the stream corridor into the adjacent ecosystems will soften environmental gradients and minimize any associated disturbances. These transitional zones encourage species diversity and buffer variable nutrient and energy flows. Although human intervention has made edges more abrupt, the conditions of naturally occurring edge vegetation can be restored through design. The plant community and landform of a restored edge should reflect the structural variations found in the reference stream corridor. To maintain a connected and contiguous vegetative cover at the edge of small gaps, taller vegetation should be designed to continue through the gap. If the gap is wider than can be breached by the tallest or widest vegetation, a more gradual edge may be appropriate.

Vertical structure of the corridor interior tends to be less diverse than that of the

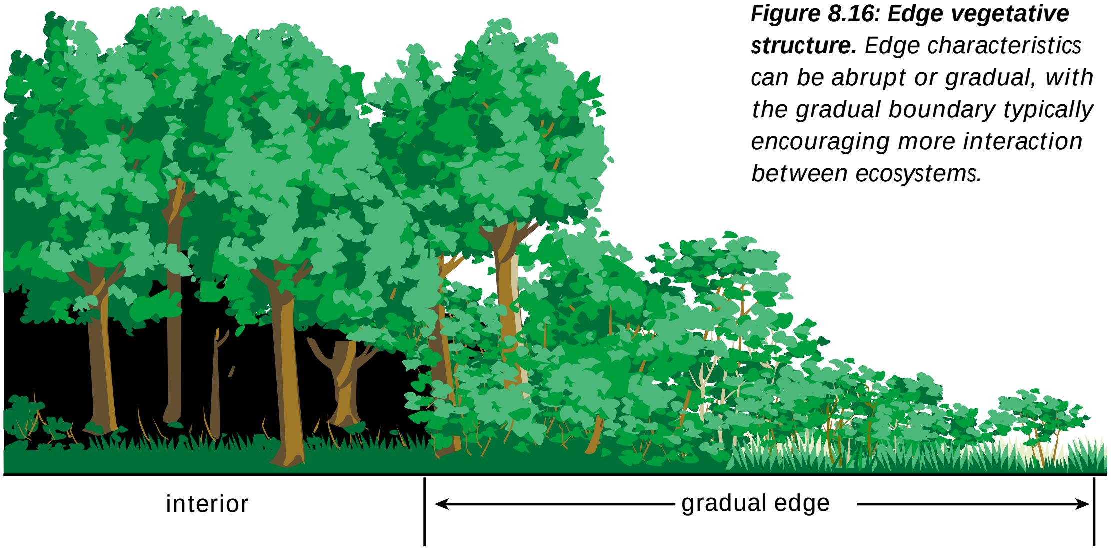


Figure 8.16: Edge vegetative structure. *Edge characteristics can be abrupt or gradual, with the gradual boundary typically encouraging more interaction between ecosystems.*

edge. This is typically observed when entering a woodlot: edge vegetation is shrubby and difficult to traverse, whereas inner shaded conditions produce a more open forest floor that allows for easier movement. Snags and downed wood may also provide important habitat functions. When designing to restore interior conditions of stream corridor vegetation, a vegetation structure should be used that is less diverse than the vegetation structure used at the edge. The reference stream corridor will yield valuable information for this aspect of design.

Influence of Hydrology and Stream Dynamics

Natural floodplain plant communities derive their characteristic horizontal diversity primarily from the organizing influence of stream migration and flooding (Brinson et al. 1981). As discussed earlier, when designing restoration of stream corridor vegetation, nearby reference conditions are generally used as models to identify the appropriate plant species and communities. However, the original cover and older existing trees might have been established before stream regulation or other changes in the watershed that affect flow and sediment characteristics.

A good understanding of current and projected flooding is necessary for design of appropriately restored plant communities within the floodplain. Water management and planning agencies are often the best sources of such data. In wildland areas, stream gauge data may be available, or on-site interpretation of landforms and vegetation may be required to determine whether floodplain hydrology has been altered through channel incision, beaver activity, or other causes. Discussions with local residents and examination of aerial photography may also provide information on water diversions, ground water depletion, and similar changes in the local hydrology.

A vegetation-hydroperiod model can be used to forecast riparian vegetation distribution (Malanson 1993). The model identifies the inundating discharges of various locations in the riparian zone and the resulting suitability of moisture conditions for desired plants. Grading plans, for example, can be adjusted to alter the area inundated by a given discharge and thus increase the area suitable for vegetation associated with a particular frequency and duration of flooding. A focus on the vegetation-hydroperiod relationship will demonstrate the following:

- The importance of moisture conditions in structuring vegetation of the riparian zone;
- The existence of reasonably well accepted physical models for calculating inundation from streamflow and the geometry of the bottomland.
- The likelihood that streamflow and inundating discharges have been altered in degraded stream systems or will be modified as part of a restoration effort.

Generally, planting efforts will be easier when trying to restore vegetation on sites that have suitable moisture conditions for the desired vegetation, such as in replacing historical vegetation on cleared sites that have unaltered streamflow and inundating discharges. Moisture suitability calculations will support designs. Sometimes the restoration objective is to restore more of the desired vegetation than the new flow conditions would naturally support. Direct manipulation by planting and controlling competition can often produce the desired results within the physiological tolerances of the desired species. However, the vegetation on these sites will be out of balance with the site moisture conditions and might require continued maintenance. Management of vegetation can also accelerate succession to a more desirable state.

Projects that require long-term supplemental watering should be avoided due to high maintenance costs and decreased potential for success. Inversely, there may be cases where the absence of vegetation, especially woody vegetation, is desired near the stream channel. Alteration of streamflow or inundating discharges might make moisture conditions on these sites unsuitable for woody vegetation.

The general concept of site suitability for plant species can be extended from moisture conditions determined by inundation to other variables determining plant distribution. For example, Ohmart and Anderson (1986) suggests that restoration of native riparian vegetation in arid southwestern river systems may be limited by unsuitable soil salinities. In many arid situations, depth to ground water might be a more direct measure of the moisture effects of streamflow on riparian sites than actual inundation. Both inundating discharge and depth to ground water are strongly related to elevation. However, depth to ground water may be the more appropriate causal variable for these rarely inundated sites, and a physical model expressing the dependence of alluvial ground water levels on streamflow might therefore be more important than a hydraulic model of surface water elevations.

Some stream corridor plant species have different requirements at different life stages. For example, plants tolerating extended inundation as adults may require a drawdown for establishment, and plants thriving on relatively high and dry sites as adults may be established only on moist surfaces near the water's edge. This can complicate what constitutes suitable moisture conditions and may require separate consideration of establishment requirements, and perhaps consideration of how sites might change over time. The application of simulation models of plant dynamics based on solving sets of explicit rules for how plant composition will change over time may become necessary as increasingly complex details of different requirements at different plant life history stages are incorporated into the evaluation of site suitability. Examples of this type of more sophisticated plant response model include van der Valk (1981) for prairie marsh species and Pearlstine et al. (1985) for bottomland hardwood tree species.

Soil Bioengineering for Floodplains and Uplands

Soil bioengineering is the use of live and dead plant materials, in combination with natural and synthetic support materials, for slope stabilization, erosion reduction, and vegetative establishment.

There are many soil bioengineering systems, and selection of the appropriate system or systems is critical to successful restoration. Reference documents should be consulted to ensure that the principles of soil bioengineering are understood and applied. The NRCS Engineering Field Handbook, Part 650 [Chapter 16, Streambank and Shoreline Protection (USDA-NRCS 1996) and Chapter 18, Soil Bioengineering for Upland Slope Protection and Erosion Reduction (USDA-NRCS 1992)] offers background and guidelines for application of this technology. A more detailed description of soil bioengineering systems is offered in Section 8.F, Streambank Stabilization Design, of this chapter and in Appendix A.

FAST FORWARD

Preview Chapter 8, Section F for more information on soil bioengineering techniques.

8.D Habitat Measures

Other measures may be used to provide structure and functions. They may be implemented as separate actions or as an integral part of the restoration plan to improve habitat, in general, or for specific species. Such measures can provide short-term habitat until overall restoration results reach the level of maturity needed to provide the desired habitat. These measures can also provide habitat that is in short supply. Greentree reservoirs, nest structures, and food patches are three examples. Beaver are also presented as a restoration measure.

Greentree Reservoirs

Short-term flooding of bottomland hardwoods during the dormant period of tree growth enhances conditions for some species (e.g., waterfowl) to feed on mast and other understory food plants, like wild millet and smartweed. Acorns are a primary food source in stream corridors for a variety of fauna, including ducks, nongame birds and mammals, turkey, squirrel, and deer. Greentree reservoirs are shallow, forested floodplain impoundments usually created by building low levees and installing outlet structures (**Figure 8.17**). They are usually flooded in early fall and drained during late March to mid-April. Draining prevents damage to overstory hardwoods (Rudolph and Hunter 1964). Most existing greentree reservoirs are in the Southwest.

The flooding of greentree reservoirs, by design, differs from the natural flood regime. Greentree reservoirs are typically flooded earlier and at depths greater than would normally occur under natural conditions. Over time, modifications of natural flood conditions can result in vegetation changes, lack of regeneration, decreased mast production, tree mortality, and disease. Proper management of green tree reservoirs requires knowledge of the local system—especially the natural flood regime—and the integration of management goals that are consistent with system requirements. Proper management of greentree reservoirs can provide

igure 8.17: Bottom-
and hardwoods
erving as a green-
ree reservoir. *Proper*
nanagement of
reentree reservoirs
equires knowledge
of the local system.

quality habitat on an annual basis, but the management plan must be well designed from construction through management for waterfowl.

Nest Structures

Loss of riparian or terrestrial habitat in stream corridors has resulted in the decline of many species of birds and mammals that use associated trees and tree cavities for nesting or roosting. The most important limiting factor for cavity-nesting birds is usually the availability of nesting substrate (von Haartman 1957), generally in the form of snags or dead limbs in live trees (Sedgwick and Knopf 1986). Snags for nest structures can be created using explosives, girdling, or topping of trees. Artificial nest structures can compensate for a lack of natural sites in otherwise suitable habitat since many species of birds will readily use nest boxes or other artificial structures. For example, along the Mississippi River in Illinois and Wisconsin, where nest trees have become scarce, artificial nest structures have been erected and constructed for double-crested cormorants using utility poles (Yoakum et al. 1980). In many cases, increases in breeding bird density have resulted from providing such structures (Strange et al. 1971, Brush 1983). Artificial nest structures can also improve nestling survival (Cowan 1959).

Nest structures must be properly designed and placed, meeting the biological needs of the target species. They should also be durable, predator-proof, and economical to build. Design specifications for nest boxes include hole diameter and shape, internal box volume, distance from the floor of the box to the opening, type of material used, whether an internal “ladder” is necessary, height of placement, and habitat type in which to place the box. Other types of nest structures include nest platforms for waterfowl and raptors; nest baskets for doves, owls, and waterfowl; floating nest structures for geese; and tire nests for squirrels. Specifications for nest structures for riparian and wetland nesting species (including numerous Picids, passerines, waterfowl, and raptors) can be found in many sources including Yoakum et al. (1980), Kalmbach et al. (1969), and various state wildlife agency and conservation publications.

Food Patches

Food patch planting is often expensive and not always predictable, but it can be carried out in wetlands or riparian systems mostly for the benefit of waterfowl. Environmental requirements of the food plants native to the area, proper time of year of introduction, management of water levels, and soil types must all be taken into consideration. Some of the more important food plants in wetlands include pondweed (Potamogeton spp.), smartweed (Polygonum spp.), duck potato, spike sedges (Carex spp.), duckweeds (Lemna spp.), coontail, alkali bulrush (Scirpus paludosus), and various grasses. Two commonly planted native species include wild rice (Zizania) and wild millet. Details on suggested techniques for planting these species can be found in Yoakum et al. (1980).

Importance of Beaver to Riparian Ecosystems

Beaver have long been recognized for their potential to influence riparian systems. In rangelands, where loss of riparian functional value has been most dramatic, the potential role of beaver in restoring degraded streams is least understood.

*Beaver dams on headwater streams can positively influence riparian function in many ways, as summarized by Olson and Hubert (1994) (**Figure 8.18**). They improve water quality by trapping sediments behind dams and by reducing stream velocity, thereby reducing bank erosion (Parker 1986). Beaver ponds can alter water chemistry by changing adsorption rates for nitrogen and phosphorus (Maret 1985) and by trapping coliform bacteria (Skinner et al. 1984). The flow regime within a watershed can also be influenced by beaver. Beaver ponds create a sponge-like effect by increasing the area where soil and water meet (**Figure 8.19**). Headwaters retain more water from spring runoff and major storm events, which is released more slowly, resulting in a higher water table and extended summer flows. This increase in water availability, both surface and subsurface, usually increases the width of the riparian zone and, consequently, favors wildlife communities that depend on that vegetation. There can be negative impacts as well, including loss of spawning habitat, increase in water temperatures beyond optimal levels for some fish species, and loss of riparian habitat.*

***Figure 8.18: Beaver dam on a headwater stream.** Beavers have many positive impacts on headwater streams.*

Richness, diversity, and abundance of birds, herpetiles, and mammals can be increased by the activities of beaver (Baker et al. 1992, Medin and Clary 1990). Beaver ponds are important waterfowl production areas and can also be used during migration (Call 1970, Ringelman 1991). In some high-elevation areas of the Rocky Mountains, beaver are solely responsible for the majority of local duck production. In addition, species of high interest, such as trumpeter swans, sandhill cranes, moose, mink, and river otters, use beaver ponds for nesting or feeding areas (Collins 1976).

Transplanting Beaver to Restore Stream Functions

Beaver have been successfully transplanted into many watersheds throughout the United States during the past 50 years. This practice was very common during the 1950s after biologists realized the loss of ecological function resulting from overtrapping of beaver by fur traders before the turn of the century. Reintroduction of beaver has restored the U.S. beaver population to 6-12 million, compared to a pre-European level of 60-400 million (Naiman et al. 1986). Much unoccupied habitat or potential habitat still remains, especially in the shrub-steppe ecosystem.

*In forested areas, where good beaver habitat already exists, reintroduction techniques are well established. The first question asked should be "If the habitat is suitable, why are beaver absent?" In the case of newly restored habitat or areas far from existing populations, reintroduction without habitat improvement might be warranted (**Figure 8.20**). Beavers are livetrapped from areas that have excess populations or from areas where they are a nuisance. It is advisable to obtain beavers from habitat that is similar to where they will be introduced to ensure*

***Figure 8.19: A beaver pond.** Beaver ponds create a sponge-like effect.*

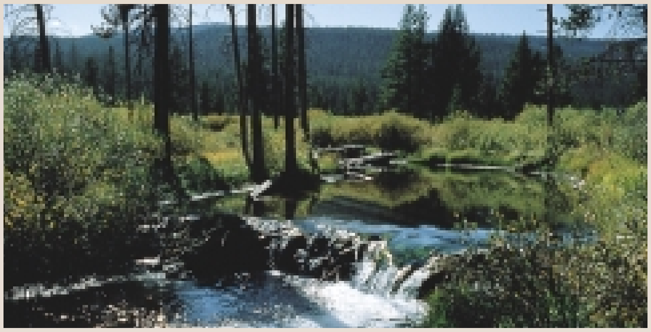


Figure 8.20: Beaver habitat. *It is advisable to obtain beaver from habitat that is similar to where they will be introduced.*

they are familiar with available food and building materials (Smith and Prichard 1992). This is particularly important in shrub-steppe habitats.

*Reintroduction into degraded riparian areas within the shrub-steppe zone is controversial. Conventional wisdom holds that a yearlong food supply must be present before introducing beaver. In colder climates, this means plants with edible bark, such as willow, cottonwood, or aspen, must be present to provide a winter food supply for beaver (**Figure 8.21**). But often these species are the goal of restoration. In some cases willows or other species can be successfully planted as described in other sections of this document. In other areas, conditions needed to sustain planted cuttings, such as a high water table and minimal competition with other vegetation, might preclude successful establishment. Transplanting beaver before willows are established may create the conditions needed to both establish and maintain riparian shrubs or trees. In these cases it may be helpful to provide beaver with a pickup truck load of aspen or other trees to use as building material at or near the reintroduction site. This may encourage beaver to stay near the site and strengthen dams built of sagebrush or other shrubs (Apple et al. 1985).*

Nuisance Beaver

Unfortunately, beaver are not beneficial in all situations, which is all too obvious to those managing damage control. In many cases where they live in close proximity to humans or features important to humans, beaver need to be removed or their damage controlled. Common problems include cutting or eating desirable vegetation, flooding roads or irrigation ditches by plugging culverts, and increasing erosion by burrowing into the banks of streams or reservoirs. In addition, beaver carry Giardia species pathogens, which can infect drinking water supplies and cause human health problems.

Control of nuisance beaver usually involves removing the problem animals directly or modifying their habitat. Beaver can be livetrapped (Bailey or Hancock traps) and relocated to a more acceptable location or killed by dead-traps (e.g., Conibear #330) or shooting (Miller 1983). In cases where the water level in a dam must be controlled to prevent flooding, a pipe can be placed through the dam with the upstream side perforated to allow water flow.

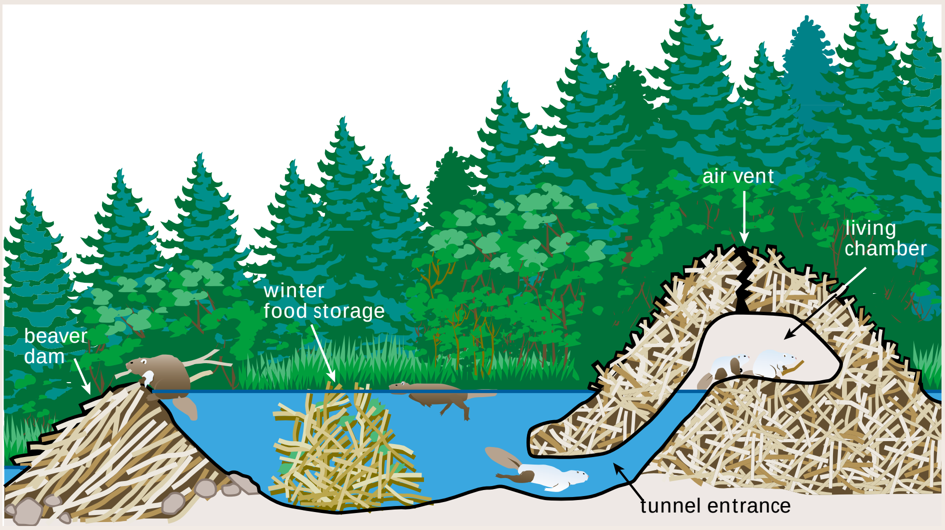


Figure 8.21: A beaver lodge. *The living chamber in a beaver lodge is above water and used year-round. Deep entrances enable beavers to obtain food from underwater caches in winter.*

8.E Stream Channel Restoration

Some disturbances to stream channels (e.g., from surface mining activities, extreme weather events, or major highway construction) are so severe that restoration within a desired time frame requires total reconstruction of a new channel. Selecting dimensions (width, depth, cross-sectional shape, pattern, slope, and alignment) for such a reconstructed channel is perhaps the most difficult component of stream restoration design. In the case of stream channel reconstruction, stream corridor restoration design can proceed along one of two broad tracks:

REVERSE

Review Chapter 4's Data Collection Planning section.

1. A single-species restoration that focuses on habitat requirements of certain life stages of species (for example, rainbow trout spawning). The existing system is analyzed in light of what is needed to provide a given quantity of acceptable habitat for the target species and life stage, and design proceeds to remedy any deficiencies noted.
2. An “ecosystem restoration” or “ecosystem management” approach that focuses design resources on the chemical, hydrologic, and geomorphic functions of the stream corridor. This approach assumes that communities will recover to a sustainable level if the stream corridor structure and functions are adequate. The strength of this approach is that it recognizes the complex interdependence between living things and the totality of their environments.

Although methods for single-species restoration design pertaining to treatments for aquatic habitat are included elsewhere in this chapter, the second track is emphasized in this section.

Procedures for Channel Reconstruction

If watershed land use changes or other factors have caused changes in sediment yield or hydrology, restoration to an historic channel condition is not recommended. In such cases, a new channel design is needed. The following procedures are suggested:

1. Describe physical aspects of the watershed and characterize its hydrologic response.

   This step should be based on data collected during the planning phase, as described in Chapter 4.
2. Considering reach and associated constraints, select a preliminary right-of-way for the restored stream channel corridor and compute the valley length and valley slope.
3. Determine the approximate bed material size distribution for the new channel.

Many of the channel design procedures described below require the designer to supply the size of bed sediments. If the project is not likely to modify bed sediments, the existing channel bed may be sampled using procedures reviewed in Chapter 7. If predisturbance conditions were different from those of the existing channel, and if those conditions must be restored, the associated sediment size distribution must be determined. This can be done by collecting representative samples of bed sediments from nearby, similar streams; by excavating to locate the predisturbance bed; or by obtaining the information from historic resources.

Like velocity and depth, bed sediment size in natural streams varies continuously in time and space. Particularly troublesome are streams with sediment size distributions that are bimodal mixtures of sand and gravel, for example. The median (D_{50}) of the overall distribution might be virtually absent from the bed. However, if flow conditions allow development of a well-defined armor layer, it might be appropriate to use a higher percentile than the median (e.g., the D_{75}) to represent the bed material size distribution. In some cases, a new channel excavated into a heterogeneous mixture of noncohesive material will develop an armor layer. In such a case, the designer must predict the likely size of the armor layer material. Methods presented by Helwig (1987) and Griffiths (1981) could prove helpful in such a situation.

4. Conduct a hydrologic and hydraulic analysis to select a design discharge or range of discharges.

Conventional channel design has revolved around selecting channel dimensions that convey a certain discharge at or below a certain elevation. Design discharge is usually based on flood frequency or duration or, in the case of canals, on downstream supply needs. Channel restoration, on the other hand, implies designing a channel similar to one that would develop naturally under similar watershed conditions.

Therefore, the first step in selecting a design discharge for restoration is not to determine the controlling elevation for flood protection but to determine what discharge controls channel size. Often this will be at or close to the 1- to 3-year recurrence interval flow. See Chapters 1 and 7 for discussions of channel-forming, effective, and design discharges. Additional guidance regarding streamflow analysis for gauged and ungauged sites is presented in Chapter 7. The designer should, as appropriate to the stream system, compute effective discharge or estimate bankfull discharge.

A sediment rating curve must be developed to integrate with the flow duration curve to determine the effective discharge. The sediment load that is responsible for shaping the channel (bed material load) should be used in the calculation of the effective discharge. This sediment load can be determined from measured data or computed using an appropriate sediment transport equation. If measured suspended sediment data are used, the wash load, typically consisting of particles less than 0.062 mm, should be deleted and only the suspended bed material portion of the suspended load used. If the bed load in the stream is considered to be only a small percentage of the total bed material load, it might be acceptable to simply use the measured suspended bed material load in the effective discharge calculations. However, if the bed load is a significant portion of the load, it should be calculated using an appropriate sediment transport function and then added to the suspended bed material load to provide an estimate of the total bed material load. If bed load measurements are available, which seldom is the case, these observed data can be used.

Flow levels and frequencies that cause flooding also need to be identified to help plan and design out-of-stream restoration measures in the rest of the stream corridor. If flood management is a constraint, additional factors that are beyond the scope of this document enter the design. Environmental features for flood control channels are described elsewhere (Hey 1995, Shields and Aziz 1992, USACE 1989a, Brookes 1988).

Channel reconstruction and stream corridor restoration are most difficult for

REVERSE

Review Chapter 1 and Chapter 7's channel-forming, effective, and design discharges sections.

incised streams, and hydrologic analyses must consider several additional factors. Incised stream channels are typically much larger than required to convey the channel-forming discharge. Restoration of an incised channel may involve raising the bottom of a stream to restore overbank flow and ecological functions of the floodplain. In this type of restoration, compatibility of restored floodplain hydrology with existing land uses must be considered.

REVERSE

Review Chapter 7's hydrologic analysis and stage-discharge relationships sections.

A second option in reconstructing incised channels is to excavate one or both sides to create a new bankfull channel with a floodplain (Hey 1995). Again, adjacent land uses must be able to accommodate the new, excavated floodplain/channel.

A third option is to stabilize the incised channel in place, and to enhance the low-flow channel for environmental benefits. The creation of a floodplain might not be necessary or possible as part of a stream restoration.

In cases where channel sizing, modification, or realignment are necessary, or where structures are required to enhance vertical or lateral stability, it is critical that restoration design also include consideration of the range of flows expected in the future. In urbanizing watersheds, future conditions may be quite different from existing conditions, with higher, sharper, peak flows.

If certain instream flow levels are required to meet restoration objectives, it is imperative that those flows be quantified on the basis of a thorough understanding of present and desired conditions. Good design practice also requires checking stream channel hydraulics and stability at discharges well above and below the design condition. Stability checks (described below) may be quite simple or very sophisticated. Additional guidance on hydrologic analysis and development of stage-discharge relationships are presented in Chapter 7.

5. Predict stable planform type (straight, meandering, or braided).

Channel planform may be classified as straight, braided, or meandering, but thresholds between categories are arbitrary since channel form can vary continuously from straight to single-channel meanders to multiple braids. Naturally straight, stable alluvial channels are rare, but meandering and braided channels are common and can display a wide range of lateral and vertical stability.

Relationships have been proposed that allow prediction of channel planform based on channel slope, discharge, and bed material size (e.g., Chang 1988), but they are sometimes unreliable (Chitale 1973, Richards 1982) and give widely varying estimates of the slope threshold between meandering and braiding. As noted by Dunne (1988), “The planform aspects of rivers are the most difficult to predict,” a sentiment echoed by USACE (1994), “... available analytical techniques cannot determine reliably whether a given channel modification will be liable to meander development, which is sensitive to difficult-to-quantify factors like bank vegetation and cohesion.”

Stable channel bed slope is influenced by a number of factors, including sediment load and bank resistance to erosion. For the first iteration, restoration designers may assume a channel planform similar to stable reference channels in similar watersheds. By collecting data for stable channels and their valleys in reference reaches, insight can be gained on what the stable configuration would be for the restoration area. The morphology of those stream types can also provide guidance or additional converging lines of evidence that the planform selected by the designer is appropriate.

After initial completion of these five steps, any one of several different paths may be taken to final design. Three approaches are summarized in **Table 8.1**. The tasks are not always executed sequentially because trial and error and reiteration are often needed.

Alignment and Average Slope

In some cases, it might be desirable to divert a straightened stream into a meandering alignment for restoration purposes. Three approaches for meander design are summarized in the adjacent box.

For cases where the design channel will carry only a small amount of bed mate-

Table 8.1: Three approaches to achieving final design. *There are variations of the final steps to a restoration design, after the first five steps described in the text are done.*

Approach A		Approach B (Hey 1994)		Approach C (Fogg 1995)	
Task	**Tools**	**Task**	**Tools**	**Task**	**Tools**
Determine meander geometry and channel alignment.[1]	Empirical formulas for meander wavelength, and adaptation of measurements from predisturbed conditions or nearly undisturbed reaches.	Determine bed material discharge to be carried by design channel at design discharge, compute bed material sediment concentration.	Analyze measured data or use appropriate sediment transport function[2] and hydraulic properties of reach upstream from design reach.	Compute mean flow, width, depth, and slope at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients.
Compute sinuosity, channel length, and slope.	Channel length = sinuosity X valley length. Channel slope= valley slope/ sinuosity.	Compute mean flow, width, depth, and slope at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients, or analytical methods (e.g. White, et.al., 1982, or Copeland, 1994).[3]	Compute or estimate flow resistance coefficient at design discharge.	Appropriate relationship between depth, bed sediment size, and resistance coefficient, modified based on expected sinuosity and bank/berm vegetation.
Compute mean flow width and depth at design discharge.[4]	Regime or hydraulic geometry formulas with regional coefficients, and resistance equations or analytical methods (e.g. tractive stress, Ikeda and Izumi, 1990, or Chang, 1988).	Compute sinuosity and channel length.	Sinuosity = valley slope/ channel slope. Channel length= sinuosity X valley length.	Compute mean channel slope and depth required to pass design discharge.	Uniform flow equation (e.g. Manning, Chezy) continuity equation, and design channel cross-sectional shape; numerical water surface profile models may be used instead of uniform flow equation.
Compute riffle spacing (if gravel bed), and add detail to design.	Empirical formulas, observation of similar streams, habitat criteria.	Determine meander geometry and channel alignment.	Lay out a piece of string scaled to channel length on a map (or equivalent procedure) such that meander arc lengths vary from 4 to 9 channel widths.	Compute velocity or boundary sheer stress at design discharge.	Allowable velocity or shear stress criteria based on channel boundary materials.
Check channel stability and reiterate as needed.	Check stability.	Compute riffle spacing (if gravel bed), and add detail to design.	Empirical formulas, observation of similar streams, habitat criteria.	Compute sinuosity and channel length.	Sinuosity = valley slope/ channel slope. Channel length= sinuosity X valley length.
		Check channel stability and reiterate as needed.	Check stability.	Compute sinuosity and channel length.	Lay out a piece of string scaled to channel length on a map (or equivalent procedure) such that meander arc lengths vary from 4 to 9 channel widths.
				Check channel stability and reiterate as needed.	Check stability.

[1] Assumes meandering planform would be stable. Sinuosity and arc-length are known.

[2] Computation of sediment transport without calibration against measured data may give highly unreliable results for a specific channel (USACE, 1994, Kuhnle, et al., 1989).

[3] The two methods listed assume a straight channel. Adjustments would be needed to allow for effects of bends.

[4] Mean flow width and depth at design discharge will give channel dimensions since design discharge is bankfull. In some situations channel may be increased to allow for freeboard. Regime and hydraulic geometry formulas should be examined to determine if they are mean width or top width.

USACE Channel Restoration Design Procedure

A systematic design methodology has been developed for use in designing restoration projects that involve channel reconstruction (USACE, WES). The methodology includes use of hydraulic geometry relationships, analytical determination of stable channel dimensions, and a sediment impact assessment. The preferred geometry is a compound channel with a primary channel designed to carry the effective or "channel forming" discharge and an overbank area designed to carry the additional flow for a specified flood discharge. Channel width may be determined by analogy methods, hydraulic geometry predictors, or analytically. Currently under development are hydraulic geometry predictors for various stream types. Once a width is determined for the effective discharge, depth and channel slope are determined analytically by balancing sediment inflow from upstream with sediment transport capacity through the restored channel. Meander wavelength is determined by analogy or hydraulic geometry relationships. Assumption of a sine-generated curve then allows calculation of channel planform. The stability of the channel design is then evaluated for the full range of expected discharges by conducting a sediment impact assessment. Refinements to the design include variation of channel widths at crossings and pools, variable lateral depths in pools, coarsening of the channel bed in riffles, and bank protection.

rial load, bed slope and channel dimensions may be selected to carry the design discharge at a velocity that will be great enough to prevent suspended sediment deposition and small enough to prevent erosion of the bed. This approach is suitable only for channels with beds that are stationary or move very infrequently—typically stable cobble- and gravel-bed streams.

Once mean channel slope is known, channel length can be computed by multiplying the straight line down-valley distance by the ratio of valley slope to channel slope (sinuosity). Meanders can then be laid out using a piece of string on a map or an equivalent procedure, such that the meander arc length L (the distance between inflection points, measured along the channel) ranges from 4 to 9 channel widths and averages 7 channel widths. Meanders should not be uniform.

The incised, straightened channel of the River Blackwater (Norfolk, United Kingdom) was restored to a meandering form by excavating a new low-level floodplain about 50 to 65 feet wide containing a sinuous channel about 16 feet wide and 3 feet deep (Hey 1995). Preliminary calculations indicated that the bed of the channel was only slightly mobile at bankfull discharge, and sediment loads were low. A carbon copy design process was used, recreating meander geometry from the mid-19th century (Hey 1994). The River Neath (Wales, United Kingdom), an active gravel-bed stream, was diverted at five locations into meandering alignments to allow highway construction. Existing slopes were maintained through each diversion, effectively illustrating a "slope-first" design (Hey 1994).

Channel Dimensions

Selection of channel dimensions involves determining average values for width and depth. These determinations are based on the imposed water and sediment discharge, bed sediment size, bank vegetation, resistance, and average bed slope. However, both width and depth may be constrained by site factors, which the designer must consider once stability criteria are met. Channel width must be less than the available corridor width, while depth is dependent on the upstream and downstream controlling elevations, resistance, and the elevation of the adjacent ground surface. In some cases, levees or floodwalls might be needed to match site constraints and depth requirements. Average dimensions determined in this step should not be applied uniformly. Instead, in the detailed design step described below, nonuniform slopes and cross sections should be specified to create converging and diverging flow and resulting physical diversity.

The average cross-sectional shape of natural channels is dependent on discharge, sediment inflow, geology, roughness, bed slope, bank vegetation, and bed and bank materials. Although bank vegetation is considered when using some of the empirical tools presented below, many of the analytical approaches do not consider the influence of bank material and vegetation or make unrealistic assumptions (e.g., banks are composed of the same material as the bed). These tools should be used with care. After initial selection of average channel width and depth, designers should consider the compatibility of these dimensions with reference reaches.

Reference Reaches

Perhaps the simplest approach to selecting channel width and depth is to use dimensions from stable reaches elsewhere in the watershed or from similar reaches in the region. The difficulty in this approach is finding a suitable reference reach. A reference reach is a reach of stream outside the project reach that is used to develop design criteria for the project reach.

A reference reach used for stable channel design should be evaluated to make sure that it is stable and has a desirable morphological and ecological condition. In addition, the reference reach must be similar enough to the desired project reach so that the comparison is valid. It must be similar to the desired project reach in hydrology, sediment load, and bed and bank material.

The term reference reach has several meanings. As used above, the reference reach is a reach that will be used as a template for the geometry of the restored channel. The width, depth, slope, and planform characteristics of the reference reach are transferred to the design reach, either exactly or by using analytical or empirical techniques to scale them to fit slightly different characteristics of the project reach (for example, a larger or smaller drainage area).

It is impossible to find an exact replica of the watershed in which the restoration work is located, and subjective judgement may play a role in determining what constitutes similarity. The level of uncertainty involved may be reduced by considering a large number of stable reaches. By classifying the reference streams, width and depth data can be grouped by stream type to reduce the scatter inherent in regional analyses.

A second common meaning of the term reference reach is a reach with a desired biological condition, which will be used as a target to strive for when comparing various restoration options. For instance, for a stream in an urbanized area, a stream with a similar drainage area in a nearby unimpacted watershed might be used as a reference reach to show what type of aquatic and riparian community might be possible in the project reach. Although it might not be possible to return the urban stream to predevelopment conditions, the characteristics of the reference reach can be used to indicate what direction to move toward. In this use of the term, a reference reach defines desired biological and ecological conditions, rather than stable channel geometry. Modeling tools such as IFIM and RCHARC (see Chapter 7) can be used to determine what restoration options come closest to replicating the habitat conditions of the reference reach (although none of the options may exactly match it).

Meander Design

Five approaches to meander design are described below, not in any intended order of priority. The first four approaches result in average channel slope being determined by meander geometry. These approaches are based on the assumption that the controlling factors in the stream channel (water and sediment inputs, bed material gradation, and bank erosional resistance) will be similar to those in the reference reach (either the restoration reach before disturbance or undisturbed reaches). The fifth approach requires determination of stream channel slope first. Sinuosity follows as the ratio of channel slope to valley slope, and meander geometry **(Figure 8.22)** is developed to obtain the desired sinuosity.

1. **Replacement of meanders exactly as found before disturbance (the carbon copy technique).** This method is appropriate if hydrology and bed materials are very similar or identical to predisturbance conditions. Old channels are often filled with cohesive soils and may have cohesive boundaries. Accordingly, channel stability may be enhanced by following a previous channel alignment.

2. **Use of empirical relationships that allow computation of meander wavelength, L, and amplitude based on channel width or discharge.** Chang (1988) presents graphical and algebraic relationships between meander wavelength, width-depth ratio, and friction factor. In addition to meander wavelength, specification of channel alignment requires meander radius of curvature (Hey 1976) and meander amplitude or channel slope. Hey (1976) also suggests that L is not usually uniquely determined by channel width or discharge. Rechard and Schaefer (1984) provide an example of development of regional formulas for meander restoration design. Chapter 7 includes a number of meander geometry relationships developed from regional data sets. Newbury and Gaboury (1993) designed meanders for a straightened stream (North Pine River) by selecting meander amplitude to fit between floodplain terraces. Meander wavelength was set at 12.4 times the channel width (on the high end of the literature range), and radius of curvature ranged from 1.9 to 2.3 times the channel width.

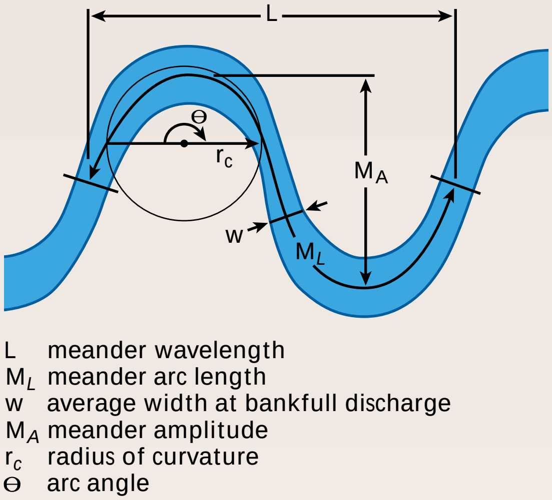


Figure 8.22: Variables used to describe and design meanders. Consistent, clear terminology is used in meander design.
Adapted from Williams 1986.

3. ***Basin-wide analysis to determine fundamental wavelength, mean radius of curvature, and meander belt width in areas "reasonably free of geologic control."*** *This approach has been used for reconstruction of streams destroyed by surface mining in subhumid watersheds of the western United States. Fourier analysis may be used with data digitized from maps to determine fundamental meander wavelength (Hasfurther 1985).*

4. ***Use of undisturbed reaches as design models.*** *If the reach targeted for restoration is closely bounded by undisturbed meanders, dimensions of these undisturbed reaches may be studied for use in the restored reach (**Figure 8.23**). Hunt and Graham (1975) describe successful use of undisturbed reaches as models for design and construction of two meanders as part of river relocation for highway construction in Montana. Brookes (1990) describes restoration of the Elbaek in Denmark using channel width, depth, and slope from a "natural" reach downstream, confirmed by dimensions of a river in a neighboring watershed with similar area, geology, and land use.*

5. ***Slope first.*** *Hey (1994) suggests that meanders should be designed by first selecting a mean channel slope based on hydraulic geometry formulas. However, correlation coefficients for regime slope formulas are always much smaller than those for width or depth formulas, indicating that the former are less accurate. Channel slope may also be determined by computing the value required to convey the design water and sediment discharges (White et al. 1982, Copeland 1994). The main weakness of this approach is that bed material sediment discharge is required by analytical techniques and in some cases (e.g., Hey and Thorne 1986) by hydraulic geometry formulas. Sediment discharges computed without measured data for calibration may be unreliable.*

Site-specific bed material samples and channel geometries are needed to apply these analytical techniques and to achieve confidence in the resulting design.

Figure 8.23: The natural meander of a stream. *Rivers meander to increase length and reduce gradient. Stream restorations often attempt to reconstruct the channel to a previous meandering condition or one "copied" from a reference reach.*

Application of Regime and Hydraulic Geometry Approaches

Typical regime and hydraulic geometry relationships are presented in Chapter 7. These formulas are most reliable for width, less reliable for depth, and least reliable for slope.

Exponents and coefficients for hydraulic geometry formulas are usually determined from data for the same stream, the same watershed, streams of a similar type, or the same physiographic region. Because formula coefficients vary, application of a given set of hydraulic geometry or regime relationships should be limited to channels similar to the calibration sites. Classifying streams can be useful in refining regime relationships (See Chapter 7's section on Stream Classification).

Published hydraulic geometry relationships are usually based on stable, single-thread alluvial channels. Hydraulic geometry relationships determined through stream classification of reference reaches can also be valuable for designing the stream restoration. Channel geometry-discharge relationships are more complex for multithread channels. Individual threads may fit the relationships if their partial bankfull discharges are used in place of the total streamflow. Also, hydraulic geometry relationships for gravel-bed rivers are far more numerous in the literature than those for sand-bed rivers.

A trial set of channel properties (average width, depth, and slope) can be evaluated by using several sets of regime and hydraulic geometry formulas and comparing results. Greatest weight should be given to formulas based on sites similar to the project reach. A logical second step is to use several discharge levels in the best-suited sets of formulas. Because hydraulic geometry relationships are most compatible with single-channel sand and gravel streams with low bed-material sediment discharge, unstable channels (aggrading or degrading profiles) can depart strongly from published relationships.

Literature references to the use of hydraulic geometry formulas for sizing restored channels are abundant. Initial estimates for width and depth for the restored channel of Seminary Creek, which drains an urban watershed in Oakland, California, were determined using regional hydraulic geometry formulas (Riley and MacDonald 1995). Hey (1994, 1995) discusses use of hydraulic geometry relationships determined using regression analyses of data from gravel bed rivers in the United Kingdom for restoration design. Newbury and Gaboury (1993) used regional hydraulic geometry relations based on drainage area to check width and depth of restored channels in Manitoba.

Hydraulic geometry formulas for sizing stream channels in restoration efforts must be used with caution since a number of pitfalls are associated with their use:

- The formulas represent hydraulic geometry only at bankfull or mean annual discharge. Designers must also select a single statistic to describe bed sediment size when using hydraulic geometry relationships. (However, refinements to the Hey and Thorne [1986] formulas for slope in Table 7.5 should be noted.)
- Downstream hydraulic geometry formulas are usually based on the bankfull discharge, the elevation of which can be extremely difficult to identify in vertically unstable channels.
- Exponents and coefficients selected for design must be based on streams with slopes, bed sediments, and bank

materials similar to the one being designed.

- The premise is that the channel shape is dependent on only one or two variables.
- Hydraulic geometry relationships are power functions with a fair degree of scatter that may prove too great for reliable engineering design. This scatter is indicative of natural variability and the influence of other variables on channel geometry.

In summary, hydraulic geometry relationships are useful for preliminary or trial selection of design channel properties. Hydraulic and sediment transport analyses are recommended for final design for the restoration.

Analytical Approaches for Channel Dimensions

Analytical approaches for designing stream channels are based on the idea that a channel system may be described by a finite number of variables. In most practical design problems, a few variables are determined by site conditions (e.g., valley slope and bed material size), leaving up to nine variables to be computed. However, designers have only three governing equations available: continuity, flow resistance (such as Manning, Chezy, and Darcy-Weisbach), and sediment transport (such as Ackers-White, Einstein, and Brownlie). Since this leaves more unknowns than there are equations, the system is indeterminate. Indeterminacy of the stable channel design problem has been addressed in the following ways:

- Using empirical relationships to compute some of the unknowns (e.g., meander parameters).
- Assuming values for one or more of the unknown variables.
- Using structural controls to hold one or more unknowns constant (e.g., controlling width with bank revetments).
- Ignoring some unknown variables by simplifying the channel system. For example, a single sediment size is sometimes used to describe all boundaries, and a single depth is used to describe water depth rather than mean and maximum depth as suggested by Hey (1988).
- Adopting additional governing equations based on assumed properties of streams with movable beds and banks. The design methods based on “extremal hypotheses” fall into this category. These approaches are discussed below under analytical approaches for channels with moving beds.

REVERSE

Review Chapter 7’s section on hydraulic geometry relationships.

Table 8.2 lists six examples of analytical design procedures for sand-bed and gravel channels. These procedures are data-intensive and would be used in high-risk or large-scale channel reconstruction work.

Table 8.2: Selected analytical procedures for stable channel design.

Stable Channel Method		Domain	Resistance Equation	Sediment Transport Equation	Third Relation
Copeland	1994	Sand-bed rivers	Brownlie	Brownlie	Left to designer’s discretion
Chang	1988	Sand-bed rivers	Various	Various	Minimum stream power
Chang	1988	Gravel-bed rivers	Bray	Chang (similar in form to Parker, Einstein)	Minimum slope
Abou-Saida and Saleh	1987	Sand-bed canals	Liu-Hwang	Einstein-Brown	Left to designer’s discretion
White et al.	1981	Sand-bed rivers	White et al.	Ackers-White	Maximum sediment transport
Griffiths	1981	Gravel-bed rivers	Griffiths	Shields entrainment	Empirical stability index

Tractive Stress (No Bed Movement)

Tractive stress or tractive force analysis is based on the idea that by assuming negligible bed material discharge ($Q_s = 0$) and a straight, prismatic channel with a specified cross-sectional shape, the inequality in variables and governing equations mentioned above is eliminated. Details are provided in many textbooks that deal with stable channel design (e.g., Richards 1982, Simons and Senturk 1977, French 1985). Because the method is based on the laws of physics, it is less empirical and region-specific than regime or hydraulic geometry formulas. To specify a value for the force "required to initiate motion," the designer must resort to empirical relationships between sediment size and critical shear stress. In fact, the only difference between the tractive stress approach for design stability analysis and the allowable stress approach is that the effect of cross-sectional shape (in particular, the bank angles) is considered in the former (**Figure 8.24**). Effects of turbulence and secondary currents are poorly represented in this approach.

Tractive stress approaches typically presume constant discharge, zero bed material sediment transport, and straight, prismatic channels and are therefore poorly suited for channels with moving beds. Additional limitations of the tractive stress design approach are discussed by Brookes (1988) and USACE (1994). Tractive stress approaches are appropriate for designing features made of rock or gravel (artificial riffles, revetments, etc.) that are expected to be immobile.

Figure 8.24: Low energy system with small bank angles. *Bank angles need to be considered when using the tractive stress approach.*

Channels with Moving Beds and Known Slope

More general analytical approaches for designing channels with bed material discharge reduce the number of variables by assuming certain constant values (such as a trapezoidal cross-sectional shape or bed sediment size distribution) and by adding new equations based on an extremal hypothesis (Bettess and White 1987). For example, in a refinement of the tractive stress approach, Parker (1978) assumed that a stable gravel channel is characterized by threshold conditions only at the junction point between bed and banks. Using this assumption and including lateral diffusion of longitudinal momentum due to fluid turbulence in the analysis, he showed that points on the bank experience stresses less than threshold while the bed moves.

Following Parker's work, Ikeda et al. (1988) derived equations for stable width and depth (given slope and bed material gradation) of gravel channels with unvegetated banks composed of noncohesive material and flat beds in motion at bankfull. Channels were assumed to be nearly straight (sinuosity < 1.2) with trapezoidal cross sections free of alternate bars. In a subsequent paper Ikeda and Izumi (1990) extended the derivation to include effects of rigid bank vegetation.

Extremal hypotheses state that a stable channel will adopt dimensions that lead to minimization or maximization of some quantity subject to constraints imposed 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 $w = k_1Q^{K_2}$; $d = K_4Q^{K5}$; 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"..

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

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

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

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

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

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

ment concentrations from 10 to 4,000 parts per million. However, this procedure is not recommended for gravel bed channels (USACE 1994). Sediment concentration at bankfull flow is required as an input variable, which limits the usefulness of this procedure. Procedures for computing sediment discharge, Q_s, are outlined in Chapter 7. Copeland (1994) found that the White et al. (1982) method for channel design was not robust for cohesive bed materials, artificial grade controls, and disequilibrium sediment transport. The method was also found inappropriate for an unstable, high-energy ephemeral sand-bed stream (Copeland 1994). However, Hey (1990) found the Ackers-White sediment transport function performed well when analyzing stability of 18 flood control channels in Britain.

The approach described by Copeland (1994) features use of the Brownlie (1981) flow-resistance and sediment-transport relations, in the form of the software package "SAM" (Thomas et al. 1993). Additional features include the determination of input bed material concentration by computing sediment concentration from hydraulic parameters for an upstream "supply reach" represented by a bed slope, a trapezoidal cross section, bed-material gradation, and a discharge. Bank and bed roughness are composited using the equal velocity method (Chow 1959) to obtain roughness for a cross section. A family of slope-width solutions that satisfy the flow resistance and sediment transport relations are then computed. The designer then selects any combination of channel properties that are represented by a point on the slope-width curve. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth. The current (1996) version of the Copeland procedure assumes a straight channel with a trapezoidal cross section and omits the portion of the cross section above side slopes when computing sediment discharge. Effects of bank vegetation are considered in the assigned roughness coefficient.

The Copeland procedure was tested by application to two existing stream channels, the Big and Colewa Creeks in Louisiana and Rio Puerco in New Mexico (Copeland 1994). Considerable professional judgment was used in selection of input parameters. The Copeland method was found inapplicable to the Big and Colewa Creeks (relatively stable perennial streams with sand-clay beds), but applicable to Rio Puerco (high-energy, ephemeral sand-bed stream with stable profile and unstable banks). This result is not surprising since all stable channel design methods developed to date presume alluvial (not cohesive or bedrock) beds.

Use of Channel Models for Design Verification

In general, a model can be envisioned as a system by whose operation the characteristics of other similar systems may be predicted. This definition is general and applies to both hydraulic (physical) and computational (mathematical) models. The use and operation of computer models has improved in recent years as a result of better knowledge of fluvial hydraulics and the development of sophisticated digital control and data acquisition systems.

Any stream corridor restoration design needs careful scrutiny because its long-term impact on the stream system is not easy to predict. Sound engineering often dictates the use of computer models or physical models to check the validity of a proposed design. Since most practitioners do not have easy access to physical modeling facilities, computer models are much more widely used. Computer models can be run in a qualitative mode with very little data or in a highly precise quantitative mode with a great deal of field data for calibration and verification.

Computer models can be used to easily and cheaply test the stability of a restoration design for a range of conditions, or for a variety of alternative channel configurations. A "model" can vary in cost from several hundred dollars to several hundred thousand dollars, depending on what model is used, the data input, the degree of precision required, and the length and complexity of the reach to be modeled. The decision as to what models are appropriate should be made by a hydraulic engineer with a background in sediment transport.

The costs of modeling could be small compared to the cost of redesign or reconstruction due to failure. If the consequences of a project failure would result in a high risk of catastrophic damage or death, and the site-specific conditions result in an unacceptable level of uncertainty when applying computer models, a physical model is the appropriate tool to use for design.

Physical Models

In some instances, restoration designs can become sufficiently complicated to exceed the capabilities of available computational models. In other situations, time might be of the essence, thus precluding the development of new computational modeling capabilities. In such cases the designer must resort to physical modeling for verification.

Depending on the scaling criteria used to achieve similitude, physical models can be classified as distorted, fixed, or movable-bed models. The theory and practice of physical modeling are covered in detail by French (1985), Jansen et al. (1979), and Yalin (1971) and are beyond the scope of this document. Physical modeling, like computational modeling, is a technology that requires specialized expertise and considerable experience. The U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, has extensively developed the technique of designing and applying physical models of rivers.

Computer Models

Computer models are structured and operated in the same way as a physical model (**Figure 8.25**). One part of the code defines the channel planform, the bathymetry, and the material properties of transported constituents. Other parts of the code create conditions at the boundaries, taking the place of the limiting walls and flow controls in the physical model. At the core of the computer code are the water and sediment transport solvers. "Turning on" these solvers is equivalent to running the physical model. At the end of the simulation run the new channel bathymetry and morphology are described by the model output. This section summarizes computational channel models that can be useful for evaluation of stream corridor restoration designs. Since it is not possible to include every existing model

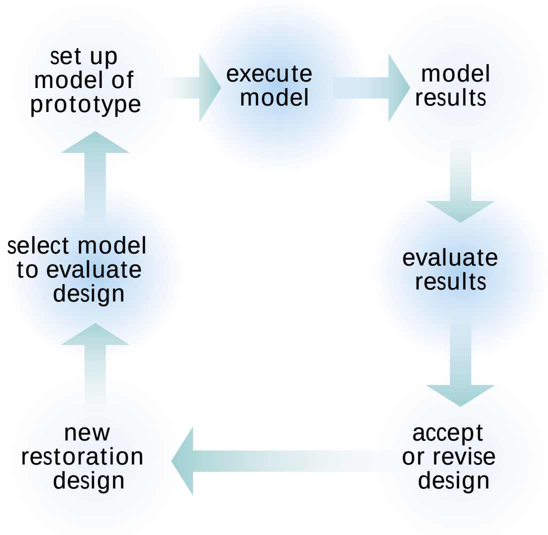


Figure 8.25: Use of models for design evaluation. *Modeling helps evaluate economics and effectiveness of alternative designs.*

Table 8.4: Examples of computational models.

Model	CHARIMA	Fluvial-12	HEC-6	TABS-2	Meander	USGS	D•O•T	GSTARS
Discretization and formulation:								
Unsteady flow | stepped hydrograph	Y | Y	Y | Y	N | Y	Y | Y	N | Y	Y | Y	N | Y	N | Y
One-dimensional | quasi-two-dimensional	Y | N	Y | Y	Y | N	N | N	N | N	N	Y | Y	Y | Y
Two-dimensional | depth-average flow	N	N	N	Y	Y	Y | Y	N	N | Y
Deformable bed | banks	Y | N	Y | Y	Y | N	Y | N	Y | N	Y | N	Y | Y	Y | Y
Graded sediment load	Y	Y	Y	Y	Y	N	Y	Y
Nonuniform grid	Y	Y	Y	Y	Y	Y	Y	Y
Variable time stepping	Y	N	Y	N	N	N	N	Y
Numerical solution scheme:								
Standard step method	N	Y	Y	N	N	N	Y	Y
Finite difference	Y	N	Y	N	Y	Y	Y	Y
Finite element	N	N	N	Y	N	N	N	N
Modeling capabilities:								
Upstream water and sediment hydrographs	Y	Y	Y	Y	Y	Y	Y	Y
Downstream stage specification	Y	Y	Y	Y	Y	N	Y	Y
Floodplain sedimentation	N	N	N	Y	N	N	N	N
Suspended | total sediment transport	Y | N	Y | N	N | Y	Y | N	N | N	N | Y	N | Y	N | Y
Bedload transport	Y	Y	Y	N	Y	N	N	Y
Cohesive sediments	N	N	Y	Y	N	Y	N	Y
Bed armoring	Y	Y	Y	N	N	N	Y	Y
Hydraulic sorting of substrate material	Y	Y	Y	N	N	N	Y	Y
Fluvial erosion of streambanks	N	Y	N	N	N	N	Y	Y
Bank mass failure under gravity	N	N	N	N	N	N	Y	N
Straight | irregular nonprismatic reaches	Y | N	Y | N	Y | N	Y | Y	N | N	N | N	Y | Y	Y | Y
Branched | looped channel network	Y | Y	Y | N	Y | N	Y | Y	N | N	N | N	N | N	N | N
Channel beds	N	Y	N	Y	Y	N	Y	N
Meandering belts	N	N	N	N	N	Y	N	N
Rivers	Y	Y	Y	Y	Y	Y	Y	Y
Bridge crossings	N	N	N	Y	N	N	N	N
Reservoirs	N	Y	Y	N	N	N	N	Y
User support:								
Model documentation	Y	Y	Y	Y	Y	Y	Y	Y
User guide | hot-line support	N | N	Y | N	Y | Y	Y | N	N | N	Y | N	N | N	Y | N

Note: Y = Yes; N = No.

in the space available, the discussion here is limited to a few selected models (**Table 8.4**). In addition, Garcia et al. (1994) review mathematical models of meander bend migration.

These models are characterized as having general applicability to a particular class of problems and are generally available for desktop computers using DOS operating systems. Their conceptual and numerical schemes are robust, having been proven in field applications, and the code can be successfully used by persons without detailed knowledge of the core computational techniques. Examples of these models and their features are summarized in Table 8.4. The acronyms in the column titles identify the following models: CHARIMA (Holly et al. 1990), FLUVIAL-12 (Chang 1990), HEC-6, TABS-2 (McAnally and Thomas 1985), MEANDER (Johannesson and Parker 1985), the Nelson/Smith-89 model (Nelson and Smith 1989), D-O-T (Darby and Thorne 1996, Osman and Thorne 1988), GSTARS (Molinas and Yang 1996) and GSTARS 2.0 (Yang et al. 1998). GSTARS 2.0 is an enhanced and improved PC version of GSTARS. HEC-6, TABS-2, and USGS are federal, public domain models, whereas CHARIMA, FLUVIAL-12, MEANDER, and D-O-T are academic, privately owned models.

With the exception of MEANDER, all the above models calculate at each computational node the fractional sediment load and rate of bed aggradation or degradation, and update the channel topography. Some of them can simulate armoring of the bed surface and hydraulic sorting (mixing) of the underlying substrate material. CHARIMA, FLUVIAL-12, HEC-6, and D-O-T can simulate transport of sands and gravels. TABS-2 can be applied to cohesive sediments (clays and silts) and sand sediments that are well mixed over the water column. USGS is specially designed for gravel bed-load transport. FLUVIAL-12 and HEC-6 can be used for reservoir sedimentation studies. GSTARS 2.0 can simulate bank failure.

Comprehensive reviews on the capabilities and performance of these and other existing channel models are provided in reports by the National Research Council (1983), Fan (1988), Darby and Thorne (1992), and Fan and Yen (1993).

Detailed Design

Channel Shape

Natural stream width varies continuously in the longitudinal direction, and depth, bed slope, and bed material size vary continuously along the horizontal plane. These variations give rise to natural heterogeneity and patterns of velocity and bed sediment size distribution that are important to aquatic ecosystems.

Widths, depths, and slopes computed during design should be adopted as reach mean values, and restored channels should be constructed with asymmetric cross sections (Hunt and Graham 1975, Keller 1978, Iversen et al. 1993, MacBroom 1981) (**Figure 8.26**). Similarly, meander planform should vary from bend to bend about average values of arc length and radius. A reconstructed floodplain should not be perfectly flat (**Figure 8.27**).

Channel Longitudinal Profile and Riffle Spacing

In stream channels with significant amounts of gravel ($D_{50} > 3$ mm) (Higginson and Johnston 1989), riffles should be associated with steep zones near meander inflection points. Riffles are not found in channels with beds of finer materials. Studies conducted by Keller and Melhorn (1978) and confirmed by Hey and Thorne (1986) indicate pool-riffle spacing should vary between 3 and 10 channel widths and average about 6 channel widths even in bedrock channels. More recent work by Roy and Abrahams (1980) and Higginson and Johnston (1989) indicates that pool-riffle spacing varies widely within a given channel.

Average riffle spacing is often (but not always) half the meander length since riffles tend to occur at meander inflection points or crossovers. Riffles sometimes appear in groups or clusters. Hey and Thorne (1986) analyzed data from 62 sites on gravel-bed rivers in the United Kingdom and found riffle spacing varied from 4 to 10 channel widths

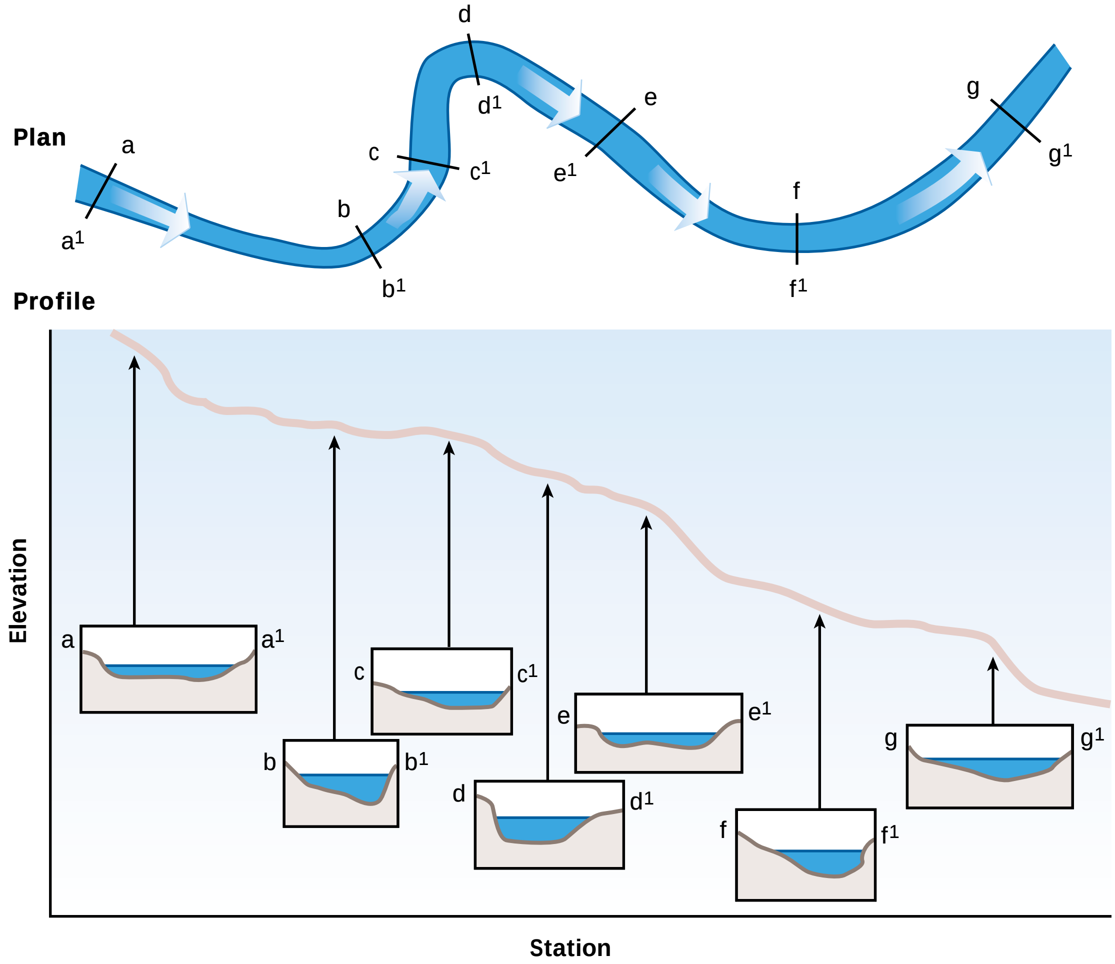


Figure 8.26: Example plan and profile of a naturally meandering stream. *Channel cross sections vary based on width, depth, and slope.*

with the least squares best fit at 6.31 channel widths. Riffle spacing tends to be nearer 4 channel widths on steeper gradients and 8 to 9 channel widths on more gradual slopes (R.D. Hey, personal communication, 1997). Hey and Thorne (1986) also developed regression formulas for riffle width, mean depth, and maximum depth.

Stability Assessment

The risk of a restored channel being damaged or destroyed by erosion or deposition is an important consideration for almost all restoration work. Designers of restored streams are confronted with rather high levels of uncertainty. In some cases, it may be wise for designers to compute risk of failure by calculating the joint probability of design assumptions being false, design equation inaccuracy, and occurrence of extreme hydrologic events during project life. Good design practice also requires checking channel performance at discharges well above and below the design condition. A number of approaches are available for checking both the vertical (bed) and horizontal (bank) stability of a designed stream. These stability checks are an important part of the design process.

Vertical (Bed) Stability

Bed stability is generally a prerequisite for bank stability. Aggrading channels are liable to braid or exhibit accelerated lateral migration in response to middle or point bar growth. Degrading channels widen explosively when bank heights and angles exceed a critical threshold specific to bank soil type. Bed aggradation can be addressed by stabilizing eroding channels upstream, controlling erosion on the watershed, or installing sediment traps, ponds (Haan et al. 1994), or debris basins (USACE 1989b). If aggradation is primarily due to deposition of fines, it can be addressed by narrowing the channel, although a narrower channel might require more bank stabilization.

If bed degradation is occurring or expected to occur, and if modification is planned, the restoration initiative should include flow modification, grade control measures, or other approaches that reduce the energy gradient or the energy of flow. There are many types of grade control structures. The applicability of a particular type of structure to a specific restoration depends on a number of factors, such as hydrologic conditions, sediment size and loading, channel morphology, floodplain and valley characteristics, availability of construction materials, ecological objectives, and time and funding constraints. For more information on various structure designs, refer to Neilson et. al. (1991), which provides a comprehensive literature review on grade control structures with an annotated bibliography. Grouted boulders can be used as a grade control structure. They are a key component in the successful restoration of the South Platte River corridor in Denver, Colorado (McLaughlin Water Engineers, Ltd., 1986).

Grade control structure stilling basins can be valuable habitats in severely degraded warm water streams (Cooper and Knight 1987, Shields and Hoover 1991). Newbury and Gaboury (1993) describe the construction of artificial riffles that serve as bed degradation controls. Kern (1992) used “river bottom ramps” to control bed degradation in a River Danube meander restoration initiative. Ferguson (1991) reviews creative designs for grade control structures that improve streamside habitat and aesthetic resources (**Figure 8.28**).

Figure 8.27: A stream meander and raised floodplain. *Natural floodplains rise slightly between a crossover and an apex of a meander.*

Horizontal (Bank) Stability

Bank stabilization may be necessary in restored channels due to floodplain land uses or because constructed banks are more prone to erosion than “seasoned” ones, but it is less than ideal if ecosystem restoration is the objective.

Figure 8.28: Grade control structure. *Control measures can double as habitat restoration devices and aesthetic features.*

Floodplain plant communities owe their diversity to physical processes that include erosion and deposition associated with lateral migration (Henderson 1986). Bank erosion control methods must be selected with the dominant erosion mechanisms in mind (Shields and Aziz 1992).

Bank stabilization can generally be grouped into one of the following three categories: (1) indirect methods, (2) surface armor, and (3) vegetative methods. Armor is a protective material in direct contact with the streambank. Armor can be categorized as stone, other self-adjusting armor (sacks, blocks, rubble, etc.), rigid armor (concrete, soil cement, grouted riprap, etc.) and flexible mattress (gabions, concrete blocks, etc.). Indirect methods extend into the stream channel and redirect the flow so that hydraulic forces at the channel boundary are reduced to a nonerosive level. Indirect methods can be classified as dikes (permeable and impermeable) and other flow deflectors such as bendway weirs, stream "barbs," and Iowa vanes. Vegetative methods can function as either armor or indirect protection and in some applications can function as both simultaneously. A fourth category is composed of techniques to correct problems caused by geotechnical instabilities.

Guidance on selection and design of bank protection measures is provided by Hemphill and Bramley (1989) and Henderson (1986). Coppin and Richards (1990), USDA-NRCS (1996), and Shields et al. (1995) provide additional detail on the use of vegetative techniques (see following section). Newly constructed channels are more susceptible to bank erosion than older existing channels, with similar inflows and geometries, due to the influence of vegetation, armoring, and the seasoning effect of clay deposition on banks (Chow 1959). In most cases, outer banks of restored or newly constructed meanders will require protection. Structural techniques are needed (e.g., Thorne et al. 1995) if immediate stability is required, but these may incorporate living components. If time permits, the new channel may be constructed "in the dry" and banks planted with woody vegetation. After allowing the vegetation several growing seasons to develop, the stream may be diverted in from the existing channel (R.D. Hey, personal communication, 1997).

Bank Stability Check

Outer banks of meanders erode, but erosion rates vary greatly from stream to stream and bend to bend. Observation of the project stream and similar reaches, combined with professional judgment, may be used to determine the need for bank protection, or erosion may be estimated by simple rules of thumb based largely on studies that relate bend migration rates to bend geometry (e.g., Apmann 1972 and review by Odgaard 1987) (**Figure 8.29**). More accurate prediction of the rate of erosion of a given streambank is at or beyond the current state of the art. No standard methods exist, but several recently developed tools are available. None of these have been used in extremely diverse settings, and users should view them with caution.

Tools for predicting bank erosion may be divided into two groups: (1) those which predict erosion primarily due to the action of water on the streambank surface and (2) those which focus on subsurface geotechnical characteristics.

Among the former is an index of streambank erodibility based on field observations of emergency spillways (Moore et al. 1994, Temple and Moore 1997). Erosion is predicted for sites

Figure 8.29: Channel exhibiting accelerated lateral migration. *Erosion of an outer bank on the Missouri River is a natural process; however, the rate of erosion should be monitored.*

where a power number based on velocity, depth, and bend geometry exceeds an erodibility index computed from tabulated values of streambank material properties. Also among this group are analytical models such as the one developed by Odgaard (1989), which contain rather sophisticated representations of flow fields, but require input of an empirical constant to quantify soil and vegetation properties. These models should be applied with careful consideration of their limitations. For example, Odgaard's model should not be applied to bends with "large curvature."

The second group of predictive tools focuses on banks that undergo mass failure due to geotechnical processes. Side slopes of deep channels may be high and steep enough to be geotechnically unstable and to fail under the influence of gravity. Fluvial processes in such a situation serve primarily to remove blocks of failed material from the bank toe, leading to a resteepened bank profile and a new cycle of failure, as shown in **Figure 8.30**. Study of bank failure processes along incised channels has

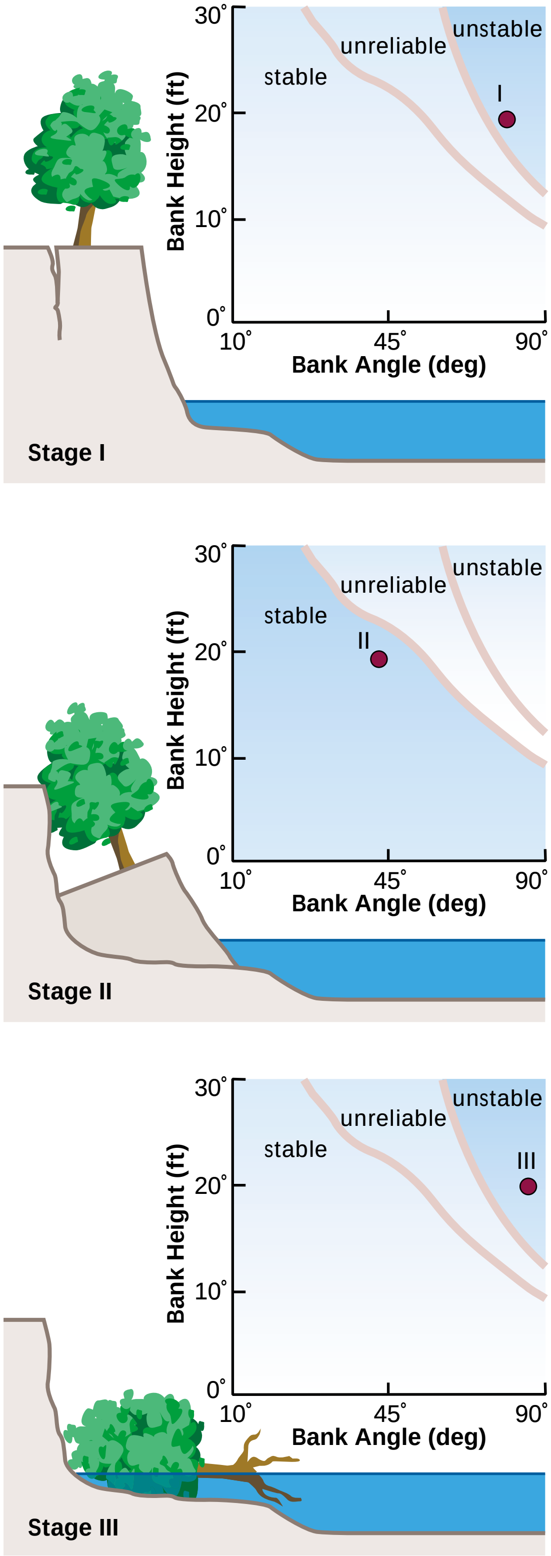


Figure 8.30: Bank failure stages. *Stability of a bank will vary from stable to unstable depending on bank height, bank angle, and soil conditions.*

led to a procedure for relating bank geometry to stability for a given set of soil conditions (Osman and Thorne 1988). If banks of a proposed design channel are to be higher than about 10 feet, stability analysis should be conducted. These analyses are described in detail in Chapter 7. Bank height estimates should allow for scour along the outside of bends. High, steep banks are also susceptible to internal erosion, or piping, as well as streambanks of soils with high dispersion rates.

Allowable Velocity Check

Fortier and Scobey (1926) published tables regarding the maximum nonscouring velocity for given channel boundary materials. Different versions of these tables have appeared in numerous subsequent documents, notably Simons and Senturk (1977) and USACE (1991). The applicability of these tables is limited to relatively straight silt and sand-bed channels with depths of flow less than 3 feet and very low bed material loads. Adjustments to velocities have been suggested for situations departing from those specified. Although slight refinements have been made, these data still form the basis of the allowable velocity approach.

Figure 8.31 contains a series of graphs that summarize the tables and aid in selecting correction factors for flow depth, sediment concentration, flow frequency, channel curvature, bank slope, and channel boundary soil properties. Use of the allowable velocity approach is not recommended for channels transporting a significant load of material larger than 1 mm. The restoration design, however, should also consider the effects of hydraulic roughness and the protection afforded by vegetation.

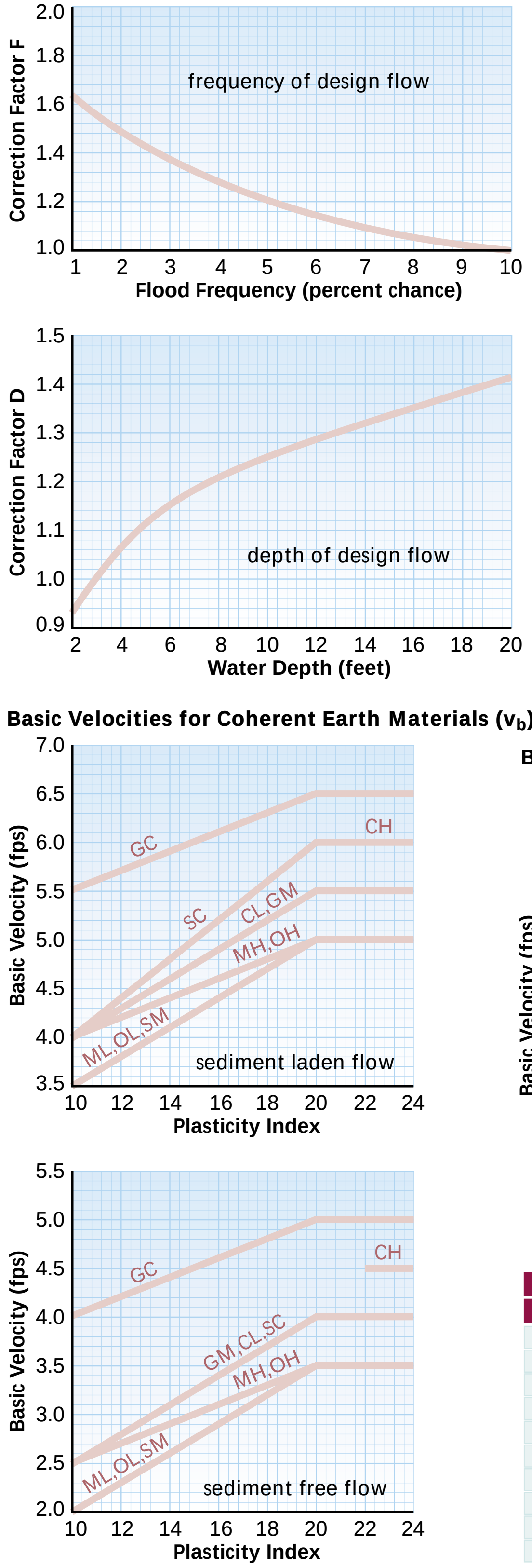
Perhaps because of its simplicity, the allowable velocity method has been used directly or in slightly modified form for many restoration applications. Miller et al. (1983) used allowable velocity criteria to design man-made gravel riffles located immediately downstream of a dam releasing a constant discharge of sediment-free water. Shields (1983) suggested using allowable velocity criteria to size individual boulders placed in channels to serve as instream habitat structures. Tarquin and Baeder (1983) present a design approach based on allowable velocity for low-order ephemeral streams in Wyoming landscapes disturbed by surface mining. Velocity of the design event (10-year recurrence interval) was manipulated by adjusting channel length (and thus slope), width, and roughness. Channel roughness was adjusted by adding meanders, planting shrubs, and adding coarse bed material. The channel width-to-depth ratio design was based on the pre-mining channel configuration.

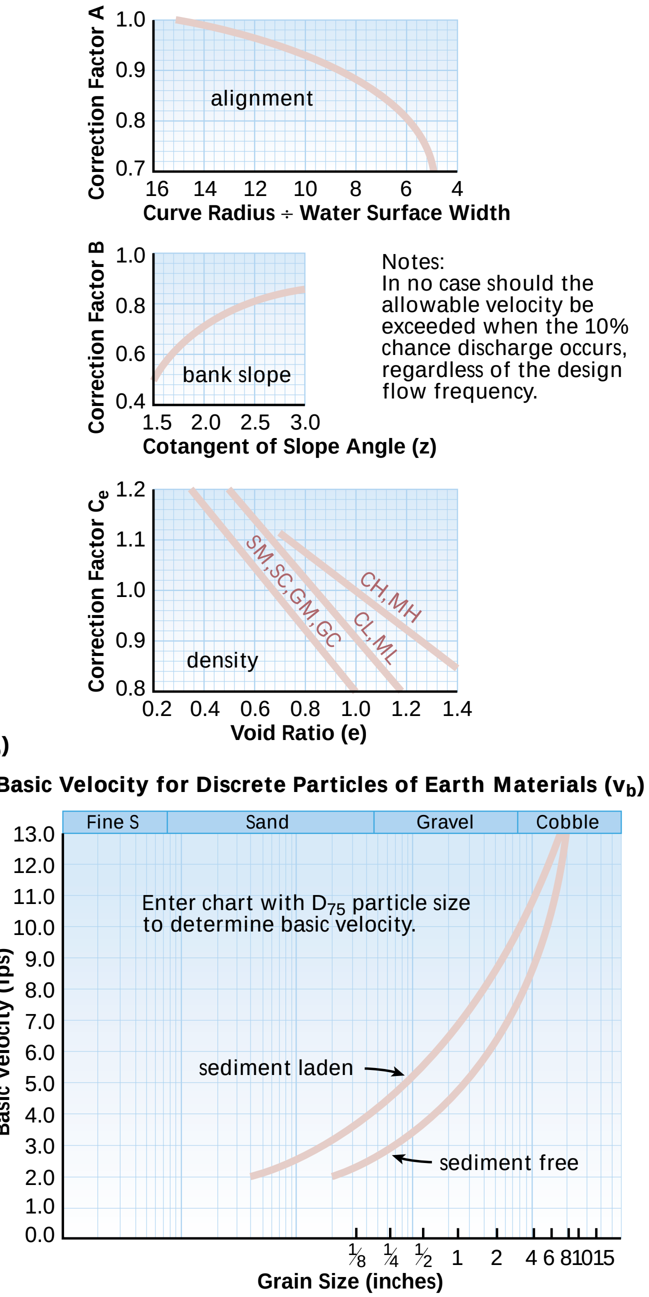
Allowable Stress Check

Since boundary shear stress is more appropriate than velocity as a measure of the forces driving erosion, graphs have also been developed for allowable shear stress. The average boundary shear stress acting on an open channel conveying a uniform flow of water is given by the product of the unit weight of water (γ, lb/ft^3) times the hydraulic radius (R, ft) times the bed slope S:

$$\tau = \gamma RS$$

Figure 8.32 is an example of allowable shear stress criteria presented in graphical form. The most famous graphical presentation of allowable shear stress criteria is the Shields diagram, which depicts conditions necessary for initial movement of noncohesive particles on





Notes:
In no case should the allowable velocity be exceeded when the 10% chance discharge occurs, regardless of the design flow frequency.

Allowable Velocities for Unprotected Earth Channels

Channel Boundary Materials	Allowable Velocity
Discrete Particles	
Sediment Laden Flow	
$D_{75} > 0.4$mm	basic velocity chart value x D x A x B
$D_{75} < 0.4$mm	2.0 fps
Sediment Free Flow	
$D_{75} > 0.2$mm	basic velocity chart value x D x A x B
$D_{75} < 0.2$mm	2.0 fps
Coherent Earth Materials	
PI > 10	basic velocity chart value x D x A x F x C_e
PI < 10	2.0 fps

Figure 8.31: Allowable velocities for unprotected earth channels. *Curves reflect practical experience in design of stable earth channels.*

Source: USDA Soil Conservation Service 1977.

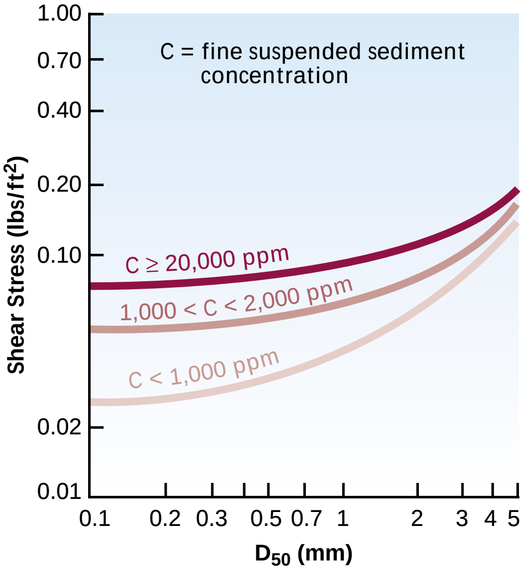


Figure 8.32: Allowable mean shear stress for channels with boundaries of noncohesive material larger than 5 mm carrying negligible bed material load. *Shear stress diminishes with increased suspended sediment concentrations.*

Source: Lane 1955.

a flat bed straight channel in terms of dimensionless variables (Vanoni 1975). The Shields curve and other allowable shear stress criteria (e.g., Figure 10.5, Henderson 1966; Figure 7.7, Simons and Senturk 1977) are based on laboratory and field data. In simplest form, the Shields criterion for channel stability is (Henderson 1966):

$$RS/[(S_s\text{-}1)D_s] < \text{a constant}$$

$$\text{for } D_s > \sim 6 \text{ mm}$$

where S_s is the specific gravity of the sediment and D_s is a characteristic bed sediment size, usually taken as the median size, D_{50}, for widely graded material. Note that the hydraulic radius, R, and the characteristic bed sediment size, D_s, must be in the same units for the Shields constant to be dimensionless. The dimensionless constant is based on measurements and varies from 0.03 to 0.06 depending on the data set used to determine it and the judgment of the user (USACE 1994).

These constant values are for straight channels with flat beds (no dunes or other bedforms). In natural streams, bedforms are usually present, and values of this dimensionless constant required to cause entrainment of bed material may be greater than 0.06. It should be noted that entrainment does not imply channel erosion. Erosion will occur only if the supply of sediment from upstream is less than that transported away from the bed by the flow. However, based on a study of 24 gravel-bed rivers in the Rocky Mountain region of Colorado, Andrews (1984) concluded that stable gravel-bed channels cannot be maintained at values of the Shields constant greater than about 0.080. Smaller Shields constant values are more conservative with regard to channel scour, but less conservative with regard to deposition. If $S_s = 2.65$, and the constant is assumed to be 0.06, the equation above simplifies to $D_{50} = 10.1RS$.

Allowable shear stress criteria are not very useful for design of channels with beds dominated by sand or finer materials. Sand beds are generally in motion at design discharge and have dunes, and their shear stress values are much larger than those indicated by the Shields criterion, which is for incipient motion on a plane bed. Allowable shear stress data for cohesive materials show more scatter than those for sands and gravels (Grissinger et al. 1981, Raudkivi and Tan 1984), and experience and observation with local channels are preferred to published charts like those shown in Chow (1959). Models of cohesive soil erosion require field or laboratory evaluation of model parameters or constants. Extrapolation of laboratory flume results to field conditions is difficult, and even field tests are subject to site-specific influences. Erosivity of cohesive soils is affected by the chemical composition of the soil, the soil water, and the stream, among other factors.

However, regional shear stress criteria may be developed from observations of channels with sand and clay beds. For example, USACE (1993) determined that reaches in the Coldwater River Watershed 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.

Allowable Stream Power or Slope

Brookes (1990) suggested the product of bankfull velocity and shear stress, which is equal to the stream power per unit bed area, as a criterion for stability in stream restoration initiatives. This is based on experience with several restoration initiatives in Denmark and the United Kingdom with sandy banks, beds of glacial outwash sands, and a rather limited range of bankfull discharges (~15 to 70 cfs). These data are plotted as squares, triangles, and circles in **Figure 8.33**.

Brookes suggested that a stream power value of 2.4 ft-lb/sec/ft^2 discriminated well between stable and unstable channels. Projects with stream powers less than about 1.0 ft-lb/sec/ft^2 failed through deposition, whereas those with stream powers greater than about 3.4 ft-lb/sec/ft^2 failed through erosion.

Since these criteria are based on observation of a limited number of sites, application to different stream types (e.g., cobble-bed rivers) should be avoided. However, similar criteria may be developed for basins of interest. For example, data points representing stable reaches in the Coldwater River watershed of northwestern Mississippi are shown in Figure 8.34 as stars. This watershed is characterized by incised, straight (channelized) sand-bed channels with cohesive banks. Slopes for stable reaches were measured in the field, and 2-year discharges were computed using a watershed model (HEC-1) (USACE 1993).

Brookes' stream power criterion is one of several region-specific stability tests. Others include criteria based on slope and shear stress. Using empirical data and observation, the Corps of Engineers has developed relationships between slope and drainage area for various watersheds in northwestern Mississippi (USACE 1989c). For example, stable reaches in three watersheds had slopes that clustered around the regression line:

$$S = 0.0041\ A^{-0.365}$$

where A is the contributing drainage area in square miles. Reaches with much steeper slopes tended to be degra-

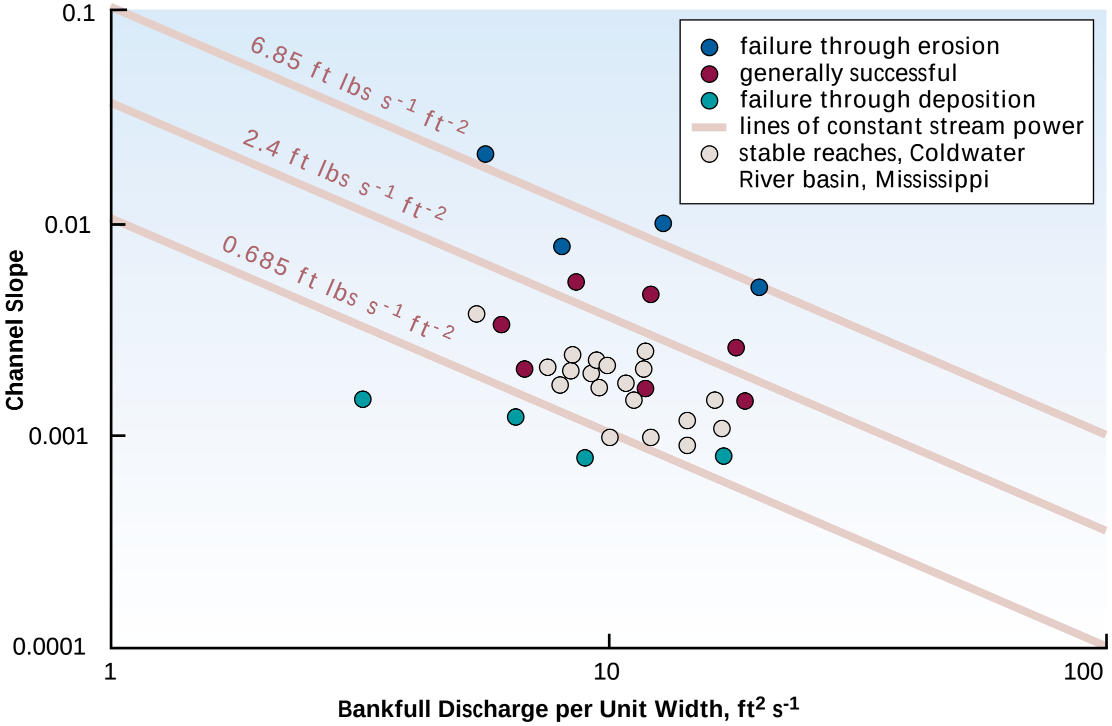


Figure 8.33: Brookes' stream power stability criteria. *Stream power is the product of bankfull velocity and shear stress.*

Allowable Shear Stress

The shape of the bed material size distribution is an important parameter for determining the threshold of motion of individual sediment sizes in a bed containing a mixture of sand and gravel. Beds composed of unimodal (particle-size distribution shows no secondary maxima) mixtures of sand and gravel were found to have a narrow range of threshold shear stresses for all sizes present on the bed surface. For unimodal beds, the threshold of motion of all grain sizes on the bed was found to be estimated adequately by using the Shields curve for the median grain size. Bed sediments composed of bimodal (particle-size distribution shows one secondary maximum) mixtures of sands and gravels were found to have threshold shear stresses that are still a function of grain size, although much less so than predicted by the Shields curve. For bed material with bimodal size distributions, using the Shields curve on individual grain sizes greater than the median size overestimates the threshold of motion and underestimates the threshold of motion for grain sizes less than the median size. Critical shear stresses for gravel beds may be elevated if gravels are tightly interlocked or imbedded.

Jackson and Van Haveren (1984) present an iterative technique for designing a restored channel based on allowable shear stress. Separate calculations were performed for channel bed and banks. Channel design included provision for gradual channel narrowing as the bank vegetation develops, and bank cohesion and resistance to erosion increase. Newbury and Gaboury (1993) use an allowable tractive force graph from Lane (1955) to check stability of channel restoration initiatives in Manitoba streams with cobble and gravel beds. Brookes (1991) gives an example of the application of this method for designing urban channels near London. From a practical standpoint, boundary shear stresses can be more difficult to measure and conceptualize than velocities (Brookes 1995). Allowable shear stress criteria may be converted to allowable velocities by including mean depth as a parameter.

The computed shear stress values are averages for the reach in question. Average values are exceeded at points, for example, on the outside of a bend.

dational, while those with more gradual slopes tended to be aggradational. Downs (1995) developed stability criteria for channel reaches in the Thames Basin of the United Kingdom based entirely on slope: channels straightened during the 20th century were depositional if slopes were less than 0.005 and erosional if slopes were greater.

Sediment Yield and Delivery

Sediment Transport

If a channel is designed using an empirical or a tractive stress approach, computation of sediment-transport capacity allows a rough check to determine whether deposition is likely to be a problem. Sediment transport relationships are heavily dependent on the data used in their development. Inaccuracy may be reduced by selecting transport functions appropriate to the stream type and bed sediment size in question. Additional confidence can be achieved by obtaining calibration data; however, calibration data are not available from a channel yet to be constructed. If the existing channel is reasonably stable, designers can compute a sediment discharge versus streamflow relationship for the existing and proposed design channels using the same sediment transport function and try to match the curves as closely as possible (USACE 1994).

If information is available regarding sediment inflows into the new channel, a multiyear sediment budget can be computed to project likely erosion and deposition and possible maintenance needs. Sediment load can also be computed, using the hydraulic properties and bed material gradations of the upstream supply reach and a suitable sediment transport function. The USACE software SAM (Copeland 1994) includes routines that compute hydraulic properties for uniform flow and sediment discharge for single cross sections of straight channels using any of 13 different sediment transport functions. Cross sections may have complex geometry and boundary materials that vary along the section. Output can be combined with a hydrograph or a flow duration curve to obtain sediment load.

HEC-6 (USACE 1993) is a one-dimensional movable-boundary, open-channel-flow numerical model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods, typically years, although applications to single flood events are possible. A continuous discharge record is partitioned into a series of steady flows of variable discharge and duration. For each discharge, a water surface profile is calculated, providing energy slope, velocity, depth, and other variables at each cross section. Potential sediment transport rates are then computed at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each reach. The amount of scour or deposition at each section is then computed, and the cross section geometry is adjusted for the changing sediment volume. Computations then proceed to the next flow in the sequence, and the cycle is repeated using the updated cross section geometry. Sediment calculations are performed by grain size fractions, allowing the simulation of hydraulic sorting and armoring.

HEC-6 allows the designer to estimate long-term response of the channel to a predicted series of water and sediment supply. The primary limitation is that HEC-6 is one-dimensional, i.e., geometry is adjusted only in the vertical direction. Changes in channel width or planform cannot be simulated. Another Federal sediment routing model is the GSTARS 2.0 (Yang et al. 1998). GSTARS 2.0 can be used for a combination of subcritical and supercritical flow computations without interruption in a semi-two-dimensional manner. The use of stream tube concept in sediment routing enables GSTARS 2.0 to simulate channel geometry changes in a semi-three-dimensional manner.

The amount and type of sediment supplied to a stream channel is an important consideration in restoration because sediment is part of the balance (i.e., between energy and material load) that determines channel stability. A general lack of sediment relative to the amount of stream power, shear stress, or energy in the flow (indexes of transport capacity) usually results in erosion of sediment from the channel boundary of an alluvial channel. Conversely, an oversupply of sediment relative to the transport capacity of the flow usually results in deposition of sediment in that reach of stream.

Bed material sediment transport analyses are necessary whenever a restoration initiative involves reconstructing a length of stream exceeding two meander wavelengths. A reconstruction that modifies the size of a cross section and the sinuosity for such a length of channel should be analyzed to ensure that upstream sediment loads can be transported through the reconstructed reach with minimal deposition or erosion. Different storm events and the average annual transported bed material load also should be examined.

Sediment Discharge Functions

The selection of an appropriate discharge formula is an important consideration when attempting to predict sediment discharge in streams. Numerous sediment discharge formulas have been proposed, and extensive summaries are provided by Alonso and Combs (1980), Brownlie (1981), Yang (1996), Bathurst (1985), Gomez and Church (1989), and Parker (1990).

Sediment discharge rates depend on flow velocity; energy slope; water temperature; size, gradation, specific gravity, and shape of the bed material and suspended-sediment particles; channel geometry and pattern; extent of bed surface covered by coarse material; rate of supply of fine material; and bed configuration. Large-scale variables such as hydrologic, geologic, and climatic conditions also affect the rate of sediment transport. Because of the range and number of variables, it is not possible to select a sediment transport formula that satisfactorily encompasses all the conditions that might be encountered. A specific formula might be more accurate than others when applied to a particular river, but it might not be accurate for other rivers.

Selection of a sediment transport formula should include the following considerations (modified from Yang 1996):

- Type of field data available or measurable within time, budget, and work hour limitations.
- Independent variables that can be determined from available data.
- Limitations of formulas versus field conditions.

If more than one formula can be used, the rate of sediment discharge should be calculated using each formula. The formulas that best agree with available measured sediment discharges should be used to estimate the rate of sediment discharge during flow conditions when actual measurements are not available.

The following formulas may be considered in the absence of any measured sediment discharges for comparison:

- Meyer-Peter and Muller (1948) formula when the bed material is coarser than 5 mm.
- Einstein (1950) formula when bed load is a substantial part of the total sediment discharge.
- Toffaleti (1968) formula for large sand-bed rivers.
- Colby (1964) formula for rivers with depths less than 10 feet and median bed material values less than 0.8 mm.
- Yang (1973) formula for fine to coarse sand-bed rivers.
- Yang (1984) formula for gravel transport when most of the bed material ranges from 2 to 10 mm.
- Ackers and White (1973) or Engelund and Hansen (1967) formula for sand-bed streams having subcritical flow.
- Laursen (1958) formula for shallow rivers with fine sand or coarse silt.

Available sediment data from a gaging station may be used to develop an empirical sediment discharge curve in the absence of a satisfactory sediment discharge formula, or to verify the sediment discharge trend from a selected formula. Measured sediment discharge or concentration should be plotted against streamflow, velocity, slope, depth, shear stress, stream power, or unit stream power. The curve with the least scatter and systematic deviation should be selected as the sediment rating curve for the station.

Sediment Budgets

A sediment budget is an accounting of sediment production in a watershed. It attempts to quantify processes of erosion, deposition, and transport in the basin. The quantities of erosion from all sources in a watershed are estimated using various procedures. Typically, the tons of erosion from the various sources are multiplied by sediment delivery ratios to estimate how much of the eroded soil actually enters a stream. The sediment delivered to the streams is then routed through the watershed.

The sediment routing procedure involves estimating how much of the sediment in the stream ends up being deposited in lakes, reservoirs, wetlands, or floodplains or in the stream itself. An analysis of the soil textures by erosion process is used to convert the tons of sediment delivered to the stream into tons of silt and clay, sand, and gravel. Sediment transport processes are applied to help make decisions during the sediment routing analysis. The end result is the sediment yield at the mouth of the watershed or the beginning of a project reach.

Table 8.5 is a summary sediment budget for a watershed. Note that the information in the table may be from measured values, from estimates based on data from similar watersheds, or from model outputs (AGNPS, SWRRBWQ, SWAT, WEPP, RUSLE, and others. Contact the NRCS National Water and Climate Data Center for more information on these models). Sediment delivery ratios are determined for watershed drainage areas, based on sediment gauge data and reservoir sedimentation surveys.

The watershed is subdivided into subwatersheds at points where significant sediment deposition occurs, such as at bridge or road fills; where stream crossings cause channel and floodplain constrictions; and at reservoirs, lakes, significant flooded areas, etc. Sediment budgets similar to the table are constructed for each subwatershed so the sediment yield to the point of deposition can be quantified.

A sediment budget has many uses, including identification of sediment sources for treatment (**Figure 8.34**). If the goal for a restoration initiative is to reduce sedimentation from a watershed, it is critical to know what type of erosion is producing the most sediment and where that erosion is occurring. In stream corridor restoration, sediment yield (both in terms of quantity and average grain size diameter) to a stream and its floodplain need to be identified and considered in designs. In channel stability investigations, the amount of sand and gravel sediment entering the stream from the watershed needs to be quantified to refine bed material transport calculations.

Example of a Sediment Budget

A simple application of a sediment transport equation in a field situation illustrates the use of a sediment budget. **Figure 8.35** shows a stream reach being evaluated for stability prior to developing a stream corridor restoration plan. Five representative channel cross sections (A, B, C, D, and E) are surveyed. Locations of the cross sections are selected to represent the reach above and below the points where tributary streams, D and E, enter the reach. Additional cross sections would need to be surveyed if the stream at A, B, C, D, or E is not typical of the reach.

An appropriate sediment transport equation is selected, and the transport capacity at each cross section for bed material is computed for the same flow conditions. Figure 8.35 shows the sediment loads in the stream and the transport capacities at each point.

Table 8.5: Example of a sediment budget for a watershed.

Protection Level	Erosion Source	Acres or Miles	Average Erosion Rate (tons/acre/year or tons/bank mile/year)	Annual Erosion (tons/ year)	Sediment Delivery Ratio (percent)	Sediment to Streams	Sediment Deposited Uplands & Floodplains (tons/year)	Sediment Delivered to Blue Stem Lake	
								(tons/ year)	(percent)
	Sheet, rill, and ephemeral gully								
Adequate	Cropland	6000	3.0	18,000	30	5400	14,380	3620	33.7
Inadequate	Cropland	1500	6.5	9750	30	2930	7790	1960	18.3
Adequate	Pasture/hayland	3400	1.0	3400	20	680	2940	460	4.3
Inadequate	Pasture/hayland	600	6.0	3600	20	720	3120	480	4.5
Adequate	Forestland	1200	0.5	600	20	120	520	80	0.7
Inadequate	Forestland	300	5.5	1650	20	330	1430	220	2.1
Adequate	Parkland	700	1.0	700	30	210	560	140	1.3
Inadequate	Parkland	0	0	0	30	0	0	0	0.0
Adequate	Other	420	2.0	840	20	170	730	110	1.0
Inadequate	Other	0	0	0	20	0	0	0	0.0
	Classic gully	N/A	N/A	600	40	240	440	160	1.5
	Streambank								
	Slight	14	50	100	700	5400	140	560	5.2
	Moderate	10.5	150	1580	100	1580	320	1260	11.7
	Severe	3.5	600	2100	100	2100	420	1680	15.7
			Total erosion	**43,520**			**Total sediment to Blue Stem Lake**	**10,730**	

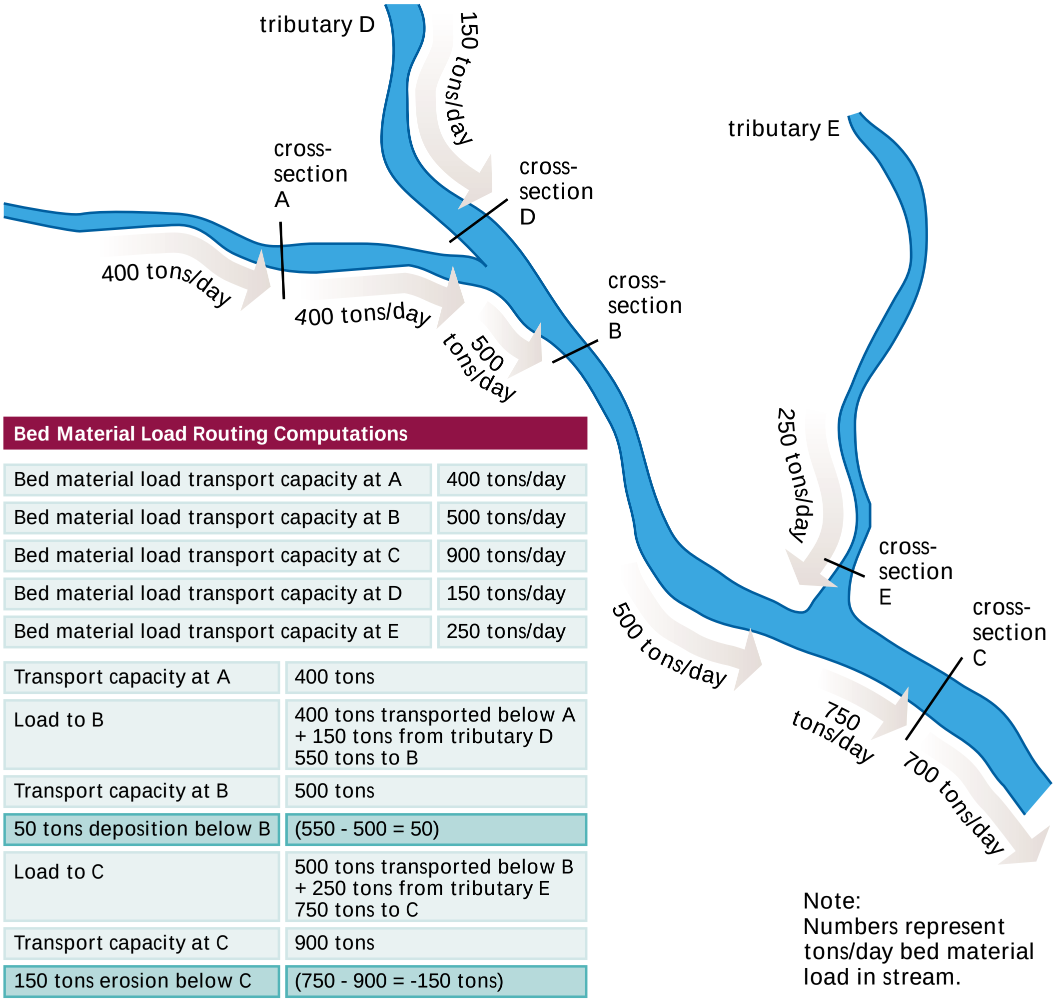
The transport capacities at each point are compared to the sediment load at each point. If the bed material load exceeds the transport capacity, deposition is indicated. If the bed material transport capacity exceeds the coarse sediment load available, erosion of the channel bed or banks is indicated.

Figure 8.35 compares the loads and transport capacities within the reach. The stream might not be stable below B due to deposition. The 50 tons/day deposition is less than 10 percent of the total bed material load in the stream. This small amount of sediment is probably within the area of uncertainty in such analyses. The stream below C probably is unstable due to the excess energy (transport capacity) causing either the banks or bottom to be eroded.

After this type of analysis is complete, the stream should be inspected for

Figure 8.34: Eroded upland area. *Upland sediment sources should be identified in a sediment budget.*

Figure 8.35:* *Sediment budget. *Stream reaches should be evaluated for stability prior to developing a restoration plan.*



Bed Material Load Routing Computations

Bed material load transport capacity at A	400 tons/day
Bed material load transport capacity at B	500 tons/day
Bed material load transport capacity at C	900 tons/day
Bed material load transport capacity at D	150 tons/day
Bed material load transport capacity at E	250 tons/day

Transport capacity at A	400 tons
Load to B	400 tons transported below A + 150 tons from tributary D 550 tons to B
Transport capacity at B	500 tons
50 tons deposition below B	(550 - 500 = 50)
Load to C	500 tons transported below B + 250 tons from tributary E 750 tons to C
Transport capacity at C	900 tons
150 tons erosion below C	(750 - 900 = -150 tons)

Note:
Numbers represent tons/day bed material load in stream.

areas where sediment is building up or where the stream is eroding. If these problem areas do not match the predictions from the calculations, the sediment transport equation may be inappropriate, or the sediment budget, the hydrology, or the channel surveys may be inaccurate.

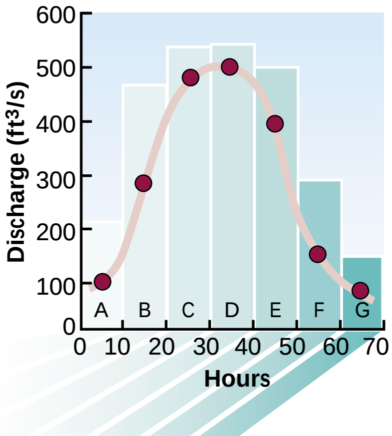
Single Storm versus Average Annual Sediment Discharge

The preceeding example predicts the amount of erosion and deposition that can be expected to occur over one day at one discharge. The bed material transport equation probably used one grain size of sediment. In reality, a variety of flows over varying lengths of time move a variety of sediment particle sizes. Two other approaches should be used to help predict the quantity of bed material sediment transported by a stream during a single storm event or over a typical runoff year.

To calculate the amount of sediment transported by a stream during a single storm event, the hydrograph for the event is divided into equal-length segments of time. The peak flow or the average discharge for each segment is determined. A spreadsheet can be developed that lists the discharges for each segment of a hydrograph in a column (**Table 8.6**). The transport capacity from the sediment rating curve for each discharge is shown in another column (**Figure 8.36**). Since the transport capacity is in tons/day, a third column should include the length of time represented by each segment of the hydro-

Table 8.6: Sediment discharges for segments of a hydrograph. *The amount of sediment discharged through a reach varies with time during a stream flow event.*

Column 1	Column 2	Column 3	Column 4	Column 5
Segment of Hydrograph	**Segment Discharge (ft^3/s)**	**Transport Capacity (tons/day)**	**Segment Time (days)**	**Actual Transport (tons)**
A	100	150	.42	62
B	280	1700	.42	708
C	483	6000	.42	2500
D	500	6500	.42	2708
E	390	4500	.42	1875
F	155	530	.42	221
G	80	90	.42	38
Total tons transported over the storm				8112



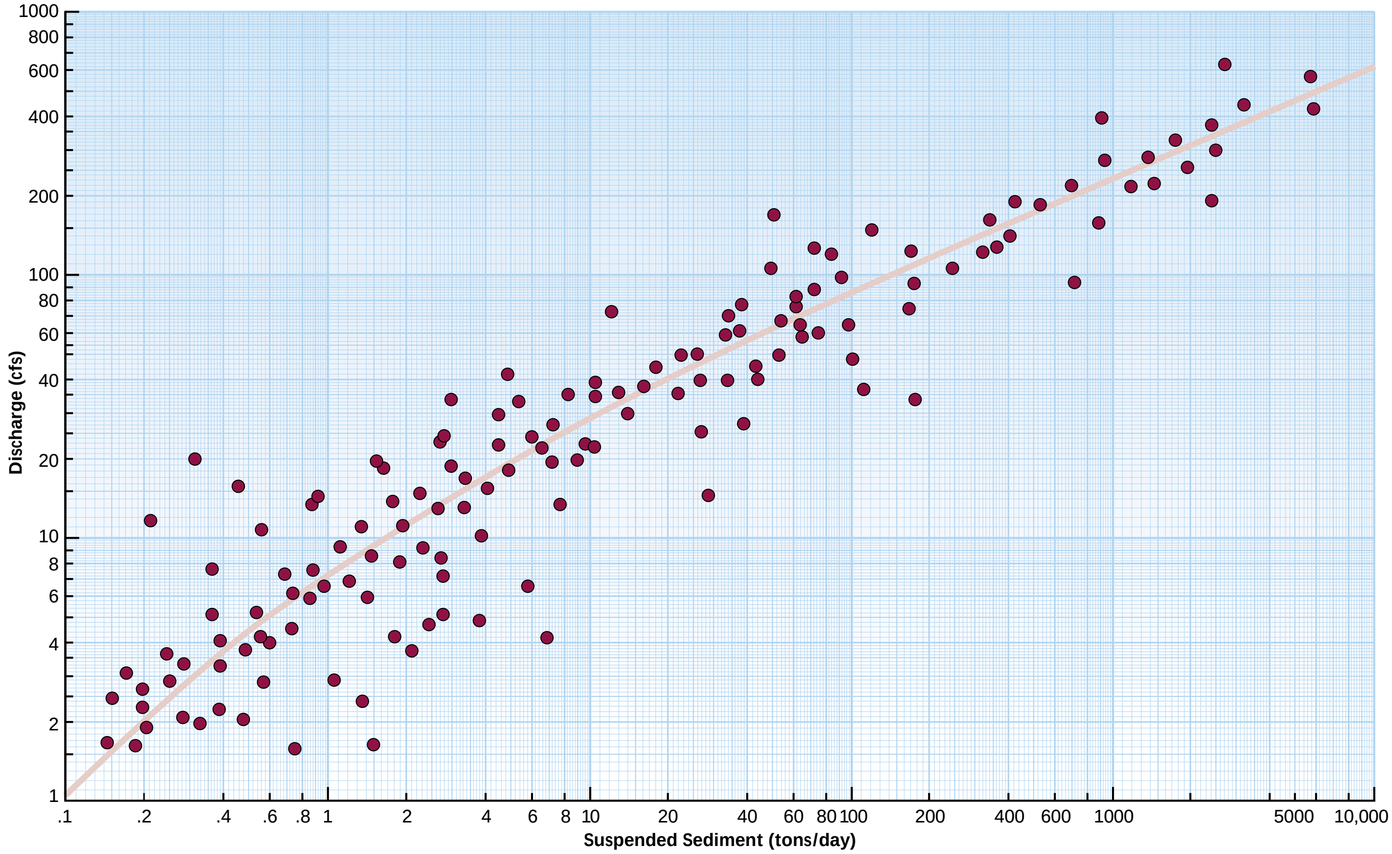


Figure 8.36: Sediment rating curve. *A "sediment rating curve" rates the quantity of sediment carried by a specific stream flow at a defined point or gage.*

graph. This column is multiplied by the transport capacity to create a final column that represents the amount of sediment that could be transported over each segment of the hydrograph. Summing the values in the last column shows the total bed material transport capacity generated by that storm.

Average annual sediment transport in a stream can be determined using a procedure very similar to the storm prediction. The sediment rating curve can be developed from predictive equations or from physical measurements. The annual flow duration curve is substituted for the segmented hydrograph. The same type of spreadsheet described above can be used, and the sum of the values in the last column is the annual sediment-transport capacity (based on predictive equations) or the actual annual sediment transport if the rating curve is based on measured data.

Sediment Discharge After Restoration

After the sediment transport analysis results have been field-checked to ensure that field conditions are accurately predicted, the same analyses are repeated for the new cross sections and slope in a reconstructed stream or stream reach. Plans and designs may be modified if the second analysis indicates significant deposition or erosion could occur in the modified reach. If potential changes in runoff or sediment yield are predicted to occur in the watershed above a potential restoration site, the sediment transport analyses should be done again based on these potential changes.

Stability Controls

The risk of a restored channel's being damaged or destroyed by erosion or deposition can be reduced if economic considerations permit installation of control measures. Control measures are also required if "natural" levels of channel instability (e.g., meander migration) are unacceptable in the restored reach.

In many cases, control measures double as habitat restoration devices or aesthetic features (Nunnally and Shields 1985, Newbury and Gaboury 1993). Control measures may be categorized as bed stabilization devices, bank stabilization devices, and hydrologic measures. Reviews of control measures are found in Vanoni (1975), Simons and Senturk (1977), Petersen (1986), Chang (1988), and USACE (1989b, 1994), and are treated only briefly here. Haan et al. (1994) provide design guidance for sediment control on small watersheds. In all cases, sediment control systems should be planned and designed with the geomorphic evolution of the watershed in mind.