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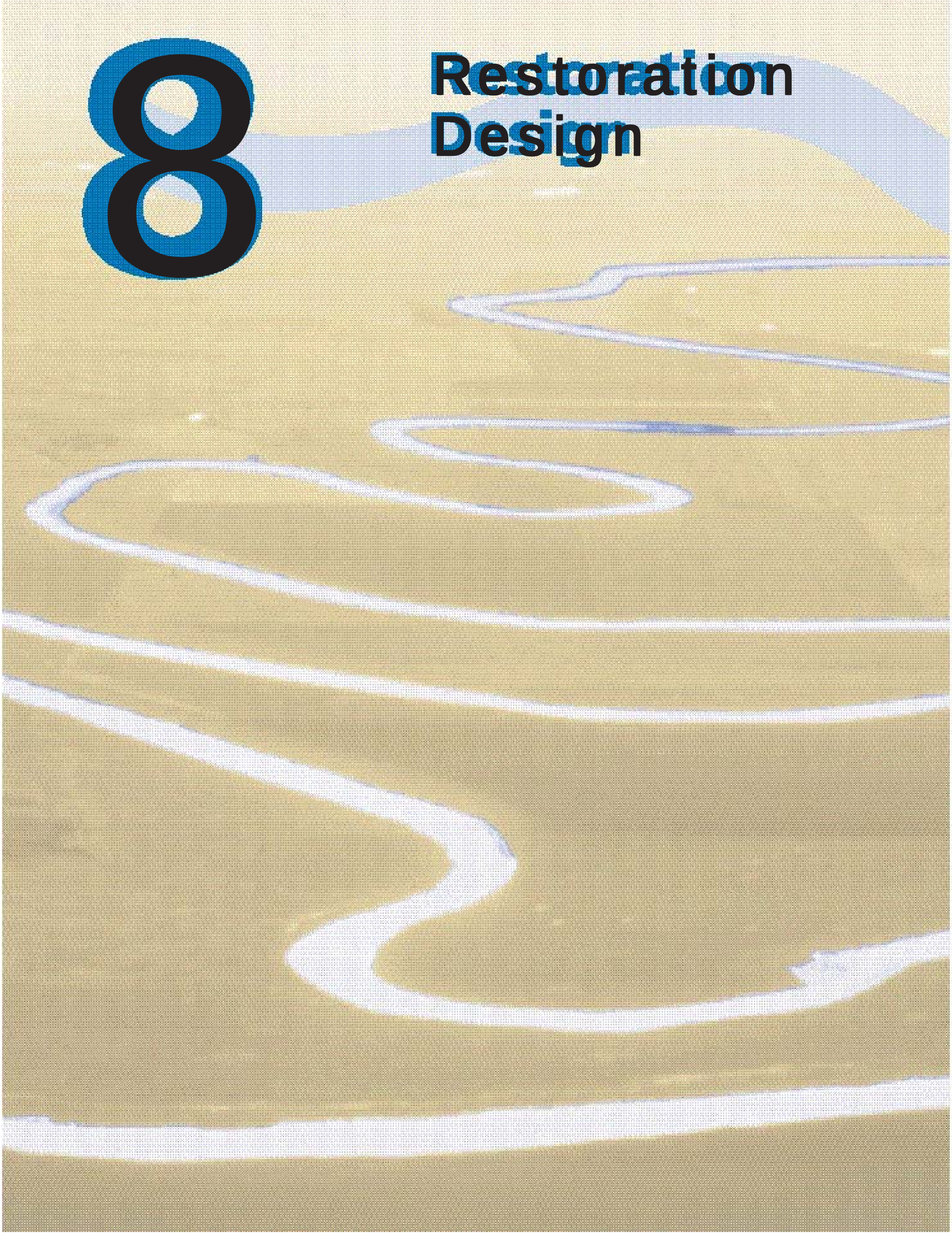
Restoration Design



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?

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

8 Restoration Design

8.A Valley Form, Connectivity, and Dimension
8.B Soil Properties
8.C Plant Communities
8.D Habitat Measures
8.E Stream Channel Restoration
8.F Streambank Restoration
8.G Instream Habitat Recovery
8.H Land Use Scenarios

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 invariable-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 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 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.

“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).

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**).

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 flo-

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

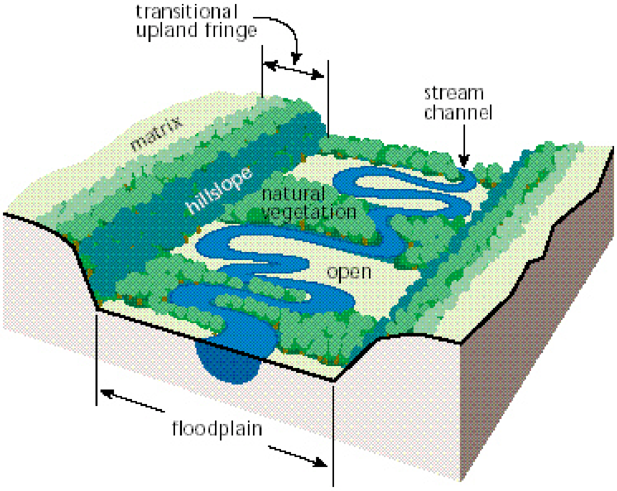


Figure 8.3: Connections across a stream corridor. *A ladder pattern of natural habitat can restore structure and functions where competing land uses prevail.* Adapted from Ecology of Greenways: Design and Function of Linear Conservation Areas. Edited by Smith and Hellmund. © University of Minnesota Press 1993.

odplains 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).

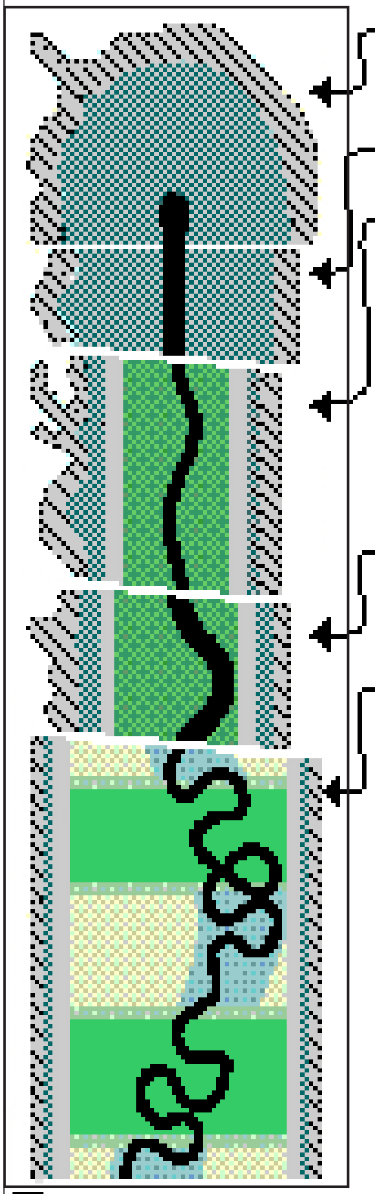
As discussed in Chapter 1, the corridor should extend across the stream, its banks, the floodplain, and the valley slopes. It should also include a portion of upland for the entire stream length to maintain functional integrity (Forman and Godron 1986).

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

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.*



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

Figure 8.4: Factors for determining minimum corridor widths. *Stream corridor functions are directly influenced by corridor width. (See Figure 8.3).* Source: Richard T.T. Forman, 1995. *Land Mosaics*, Cambridge University Press. Reprinted with the permission of Author and Cambridge University Press.

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).

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 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.

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.

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.*

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

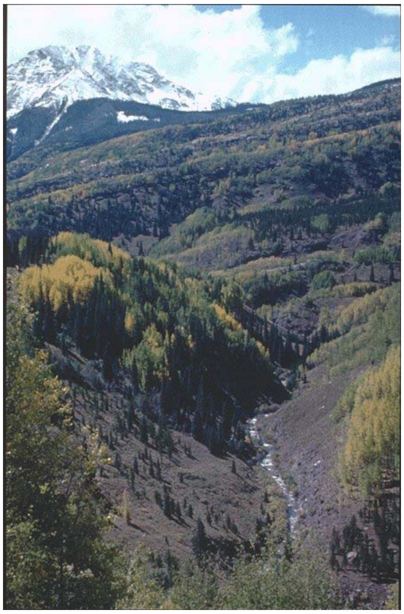


Figure 8.6: Distinct vegetation zones along a mountain stream. *Variable soils result in diverse plant communities.*

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, service-berry, 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.

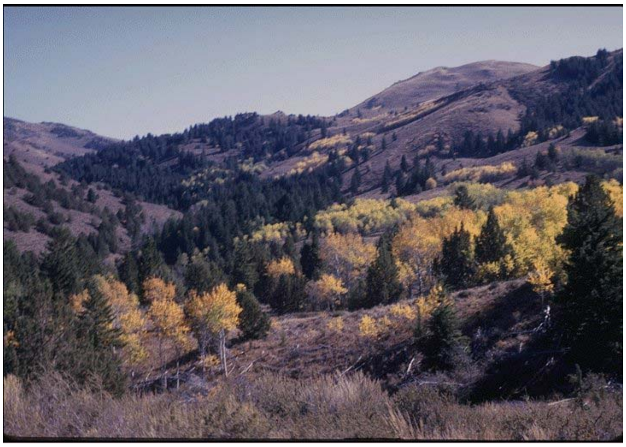


Figure 8.8: Stream corridor vegetation. *Vegetation is a fundamental controlling factor in the functioning of stream corridors.*

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 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 bottomland 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 cotton-woods and willows, the emphasis might be to emulate natural patterns of colonization by planting groves of particular species rather than mixed

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

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.*

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 stand-point, 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, fair-ways, 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*

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.

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 non-native 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).

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.*

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.

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.

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,

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).

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

Tennessee Valley Authority Floodplain Reforestation Projects 50 Years Later

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

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 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.

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.*

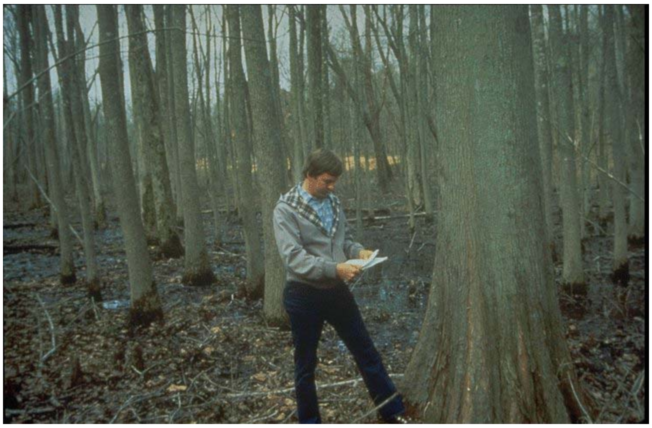


Figure 8.14: Kentucky Reservoir watershed in 1991. *Thriving bottomland hardwood forest.*

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 migration 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.

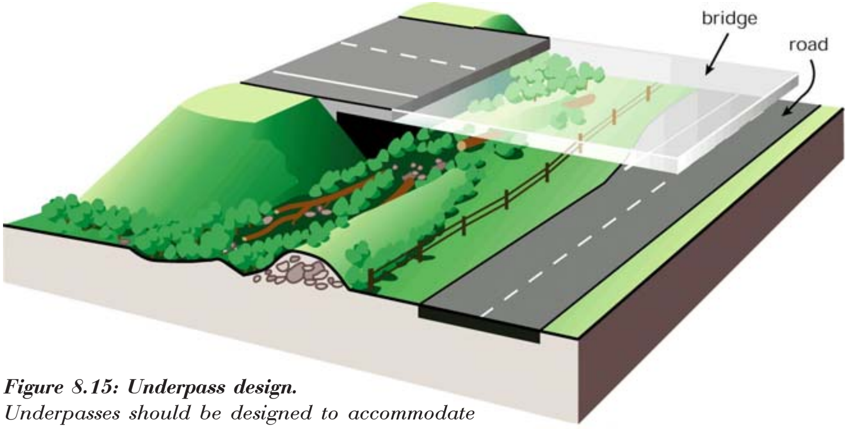


Figure 8.15: Underpass design.
Underpasses should be designed to accommodate both vehicular traffic and movement of small fauna.

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.

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 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.

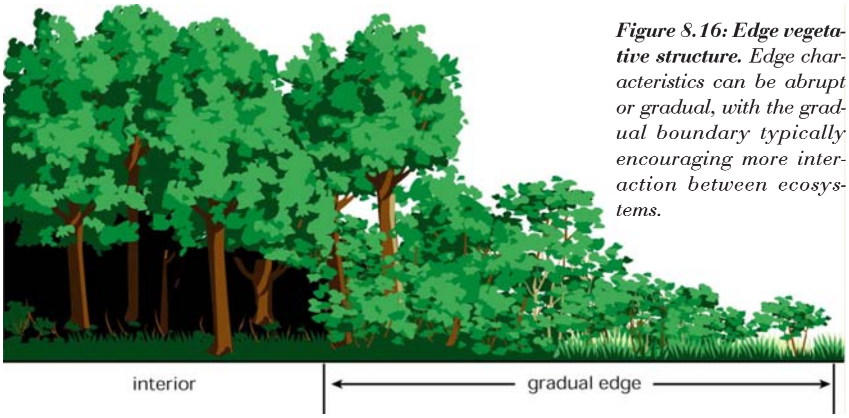


Figure 8.16: Edge vegetative structure. *Edge characteristics can be abrupt or gradual, with the gradual boundary typically encouraging more interaction between ecosystems.*

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 stream-flow 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, Stream-bank 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 hard-woods (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 quality habitat on an annual basis, but the management plan must be well designed from construction through management for waterfowl.

Figure 8.17: Bottom-and hardwoods serving as a green-tree reservoir. *Proper management of green-tree reservoirs requires knowledge of the local system.*

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).

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:

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.

REVERSE

Review Chapter 4's
Data Collection Planning section.

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).*

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

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.*

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).

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

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 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,

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

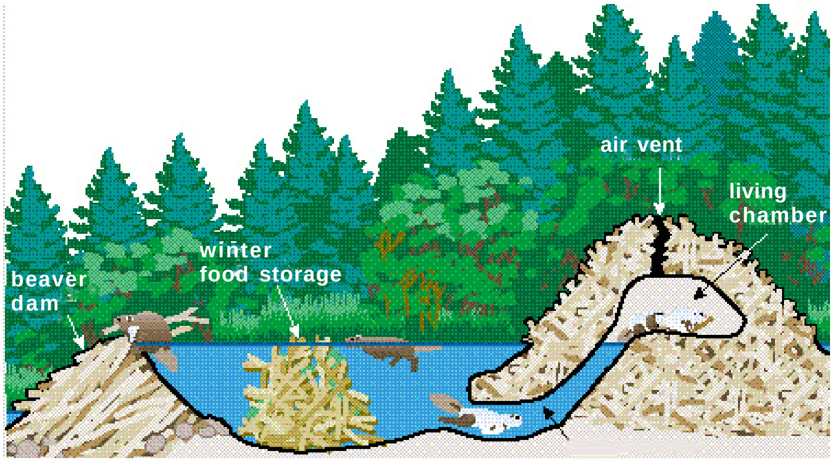


Figure 8.21: A beaver lodge. *The living chamber in a beaver lodge is above water and used year-round. Deep entrances enable beavers to obtain food from underwater caches in winter.*

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.*

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.

REVERSE

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

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 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.

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 techni-

REVERSE

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

ques 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.

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.

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 box in the previous page.

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

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.

ble 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).

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.

REVERSE

Review Chapter 7's section on hydraulic geometry relationships.

Meander Design

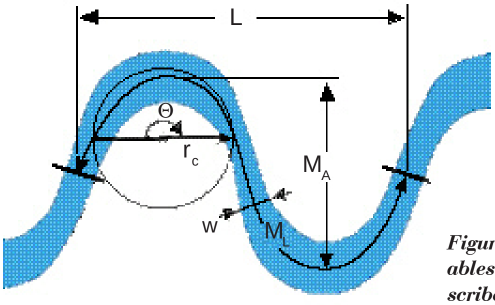
Five approaches to meander design are described below, not in any intended order of priority. The first four approaches result in average channel slope being determined by meander geometry. These approaches are based on the assumption that the controlling factors in the stream channel (water and sediment 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.



L	meander wavelength
M_L	meander arc length
w	average width at bankfull discharge
M_A	meander amplitude
r_c	radius of curvature
Θ	arc angle

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.*

- 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.

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.

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

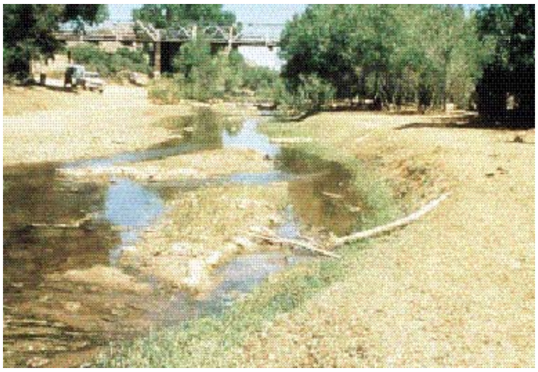


Figure 8.24: Low energy system with small bank angles. *Bank angles need to be considered when using the tractive stress approach.*

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

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.

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 se-

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	$1.0\ k_4$**	0.45
Thorne et al.	1988	Same as for Thorne and Hey 1986	Gravel-bed rivers	$1.905 + k_1$***	0.47	$0.2077 + k_4$***	0.42
		Adjustments for bank vegetation[a]	Grassy banks with no trees or shrubs	$w = 1.46\ w_c - 0.8317$		$d = 0.8815\ d_c + 0.2106$	
			1-5% tree and shrub cover	$w = 1.306\ w_c - 8.7307$		$d = 0.5026\ d_c + 1.7553$	
			5-50% tree and shrub cover	$w = 1.161\ w_c - 16.8307$		$d = 0.5413\ d_c + 2.7159$	
			Greater than 50% tree and shrub cover, or incised into flood plain	$w = 0.9656\ w_c - 10.6102$		$d = 0.7648\ d_c + 1.4554$	

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

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

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

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

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

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

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

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

lected.

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 sediment 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 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.

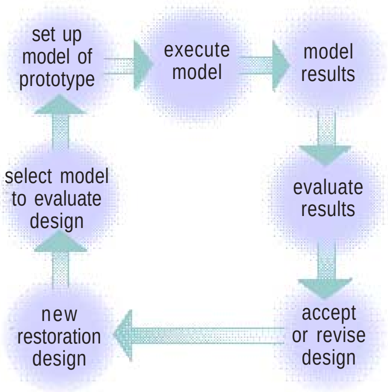


Figure 8.25: Use of models for design evaluation. *Modeling helps evaluate economics and effectiveness of alternative designs.*

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 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

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.

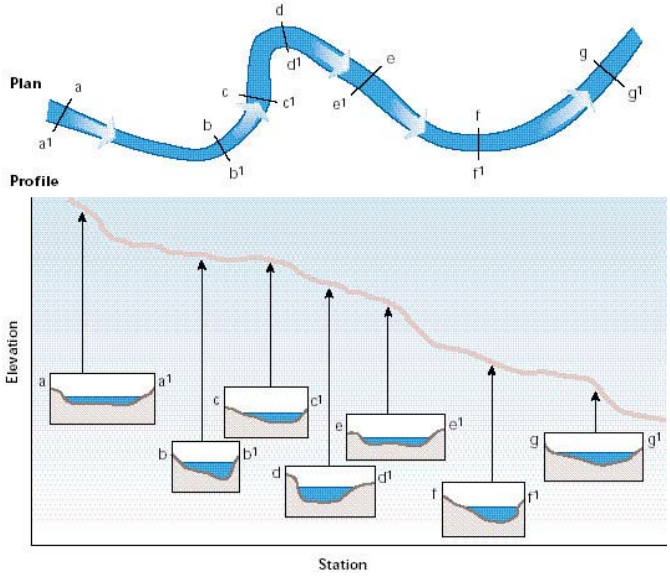


Figure 8.26: Example plan and profile of a naturally meandering stream. *Channel cross sections vary based on width, depth, and slope.*

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

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**).

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.

Floodplain plant communities owe their diversity to physical processes that include erosion and deposition associated with lateral migration

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

(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 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 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,

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.*

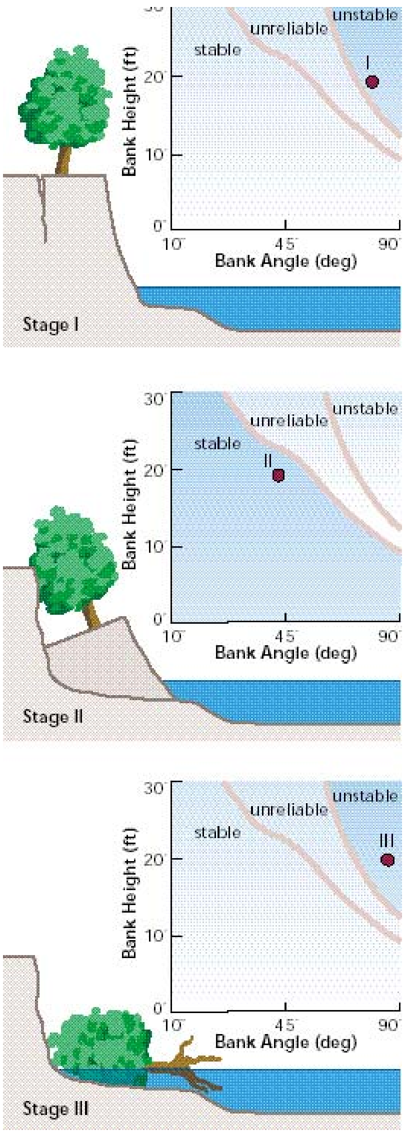
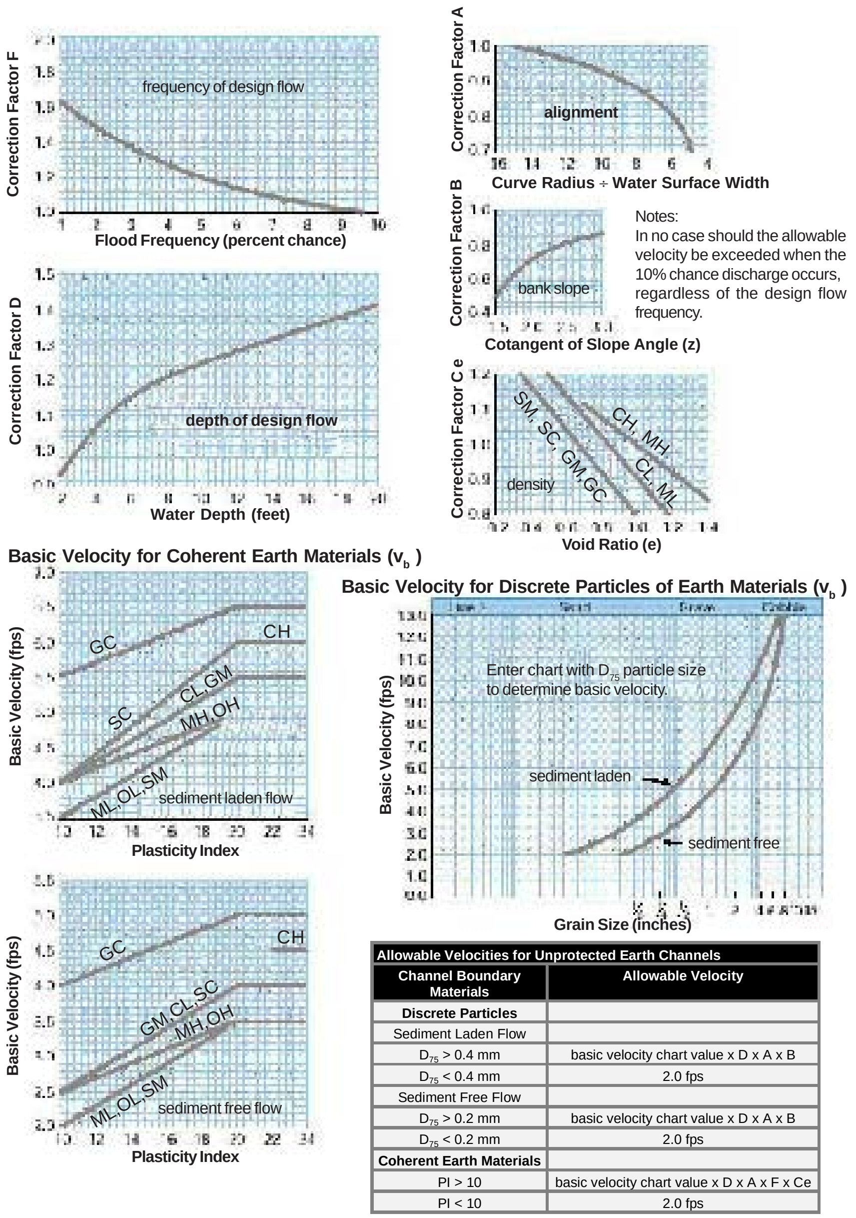


Figure 8.30: Bank failure stages. *Stability of a bank will vary from stable to unstable depending on bank height, bank angle, and soil conditions.*

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 premining channel configuration.



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 Ce
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.

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:

$$\tau = \gamma R S$$

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 non-cohesive particles on 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):

$$RS/[(S_S - 1)D_S] < \text{a constant}$$
$$\text{for } D_S > \sim 6 \text{ mm}$$

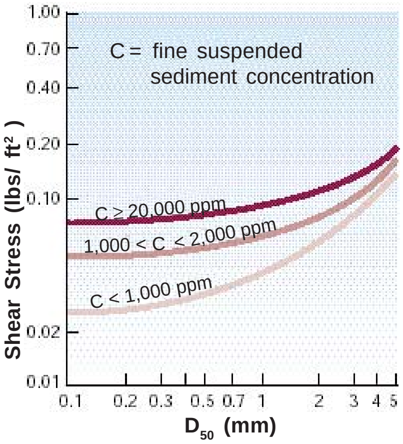


Figure 8.32: Allowable mean shear stress for channels with boundaries of non-cohesive material larger than 5 mm carrying negligible bed material load. *Shear stress diminishes with increased suspended sediment concentrations.*
Source: Lane 1955.

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 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 black circles. 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 degradational, 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.

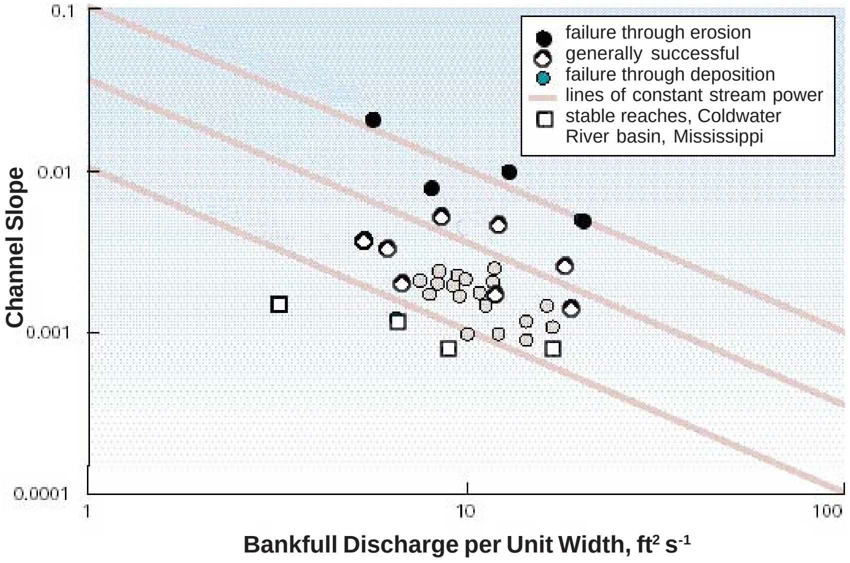


Figure 8.33: ***Brookes' stream power stability criteria.*** *Stream power is the product of bankfull velocity and shear stress.*

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 balan-

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.

ce (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,

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	18000	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	0	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**	

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.

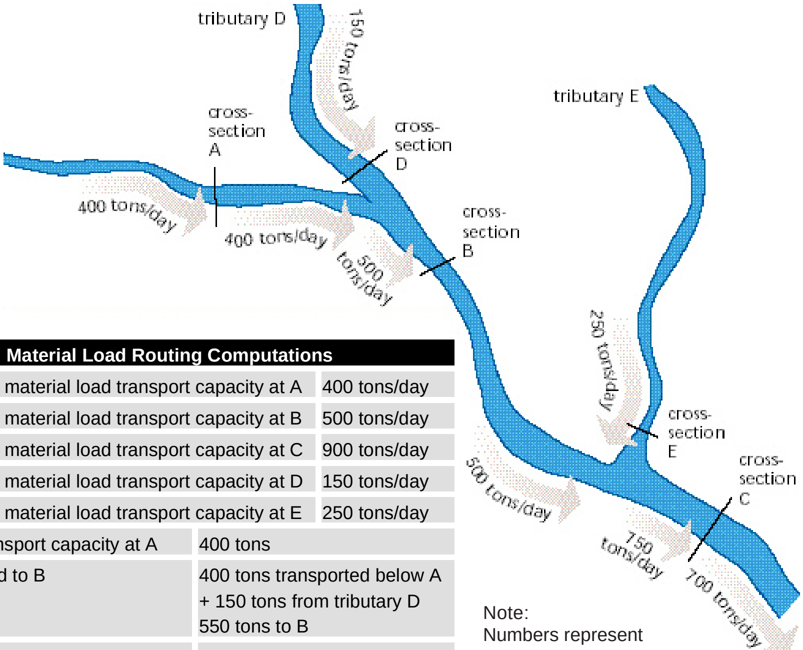
Example of a Sediment Budget

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.

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, ero-

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



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.

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

sion 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 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

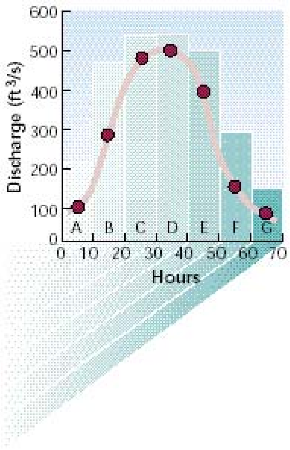
The preceeding example predicts the amount of erosion and deposition that can be expected to occur over one day at one discharge. The bed material transport equation probably used one grain size of sediment. In reality, a variety of flows over varying lengths of time move a variety of sediment particle 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 hydrograph. 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 cur-

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



ve 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.

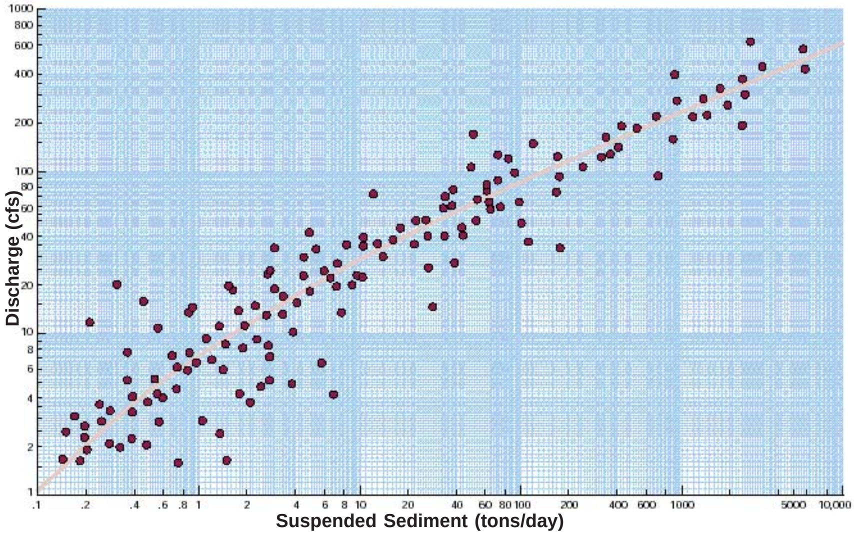


Figure 8.36: Sediment rating curve. *A "sediment rating curve" rates the quantity of sediment carried by a specific stream flow at a defined point or gage.*

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.

8.F Streambank Restoration

Even where streams retain relatively natural patterns of flow and flooding, stream corridor restoration might require that streambanks be temporarily (years to decades) stabilized while floodplain vegetation recovers. The objective in such instances is to arrest the accelerated erosion often associated with unvegetated banks, and to reduce erosion to rates appropriate for the stream system and setting. In these situations, the initial bank protection may be provided primarily with vegetation, wood, and rock as necessary (refer to Appendix A).

In other cases, land development or modified flows may dictate the use of hard structures to ensure permanent stream stability, and vegetation is used primarily to address specific ecological deficiencies such as a lack of channel shading. In either case (permanent or temporary bank stabilization), stream-flow projections are used (as described in Chapter 7) to determine the degree to which vegetation must be supplemented with more resistant materials (natural fabrics, wood, rock, etc.) to achieve adequate stabilization.

The causes of excessive erosion may be reversible through changes in land use, livestock management, floodplain restoration, or water management. In some cases, even normal rates of bank erosion and channel movement might be considered unacceptable due to adjacent development, and vegetation might be used primarily to recover some habitat functions in the vicinity of "hard" bank stabilization measures. In either case, the considerations discussed above with respect to soils, use of native plant species, etc., are applicable within the bank zone. However, a set of specialized techniques can be employed to help ensure plant establishment and improve habitat conditions.

As discussed earlier in this chapter, integration of woody vegetative cuttings, independently or in combination with other natural materials, in streambank erosion control projects is generally referred to as soil bioengineering. Soil-bioengineered bank stabilization systems have not been standardized for general application under particular flow conditions, and the decision as to whether and how to use them requires careful consideration of a variety of factors. On larger streams or where erosion is severe, an effective approach involves a team effort that includes expertise in soils, biology, plant sciences, landscape architecture, geology, engineering, and hydrology.

Soil bioengineering approaches usually employ plant materials in the form of live woody cuttings or poles of readily sprouting species, which are inserted deep into the bank or anchored in various other ways. This serves the dual purposes of resisting washout of plants during the early establishment period, while providing some immediate erosion protection due to the physical resistance of the stems. Plant materials alone are sufficient on some streams or some bank zones, but as erosive forces increase, they can be combined with other materials such as rocks, logs or brush, and natural fabrics (**Figure 8.37**). In some cases, woody debris is incorporated specifically to improve habitat characteristics of the bank and near-bank channel zones.

Preliminary site investigations (see **Figure 8.38**) and engineering analyses must be completed, as described in Chapter 7, to determine the mode of bank failure and the feasibility of using vegetation as a component of bank stabilization work. In addition to the technical analyses of flows and soils, preliminary investigations must include consideration of access, maintenance, urgency, and availability of materials.

Generalizations regarding water levels and flow velocities should be taken only as indications of the experiences reported from various bank stabilization projects. Any particular site must be evaluated to determine how vegetation can or cannot be used. Soil cohesiveness, the presence of gravel lenses, ice accumulation patterns, the amount of sunlight reaching the bank, and the ability to ensure that grazing will be precluded are all considerations in assessing the suitability of vegetation to achieve bank stabilization. In addition, modified flow patterns may make portions of the bank inhospitable to plants because of inappropriate timing of inundation rather than flow velocities and durations (Klimas 1987). The need to extend protection well beyond the immediate focus of erosion and to protect against flanking is an important design consideration.

As noted in Section 8.E, streambank stabilization techniques can generally be classified as armor, indirect methods, or vegetative methods. The selection of the appropriate stabilization technique is extremely important and can be expressed in terms of the factors discussed below.

Effectiveness of Technique

The inherent factors in the properties of a given bank stabilization technique, and in the physical characteristics of a proposed work site, influence the suitability of that technique for that site. Effectiveness refers to the suitability and adequacy of the technique. Many techniques can be designed to adequately solve a specific bank stability problem by resisting erosive for-

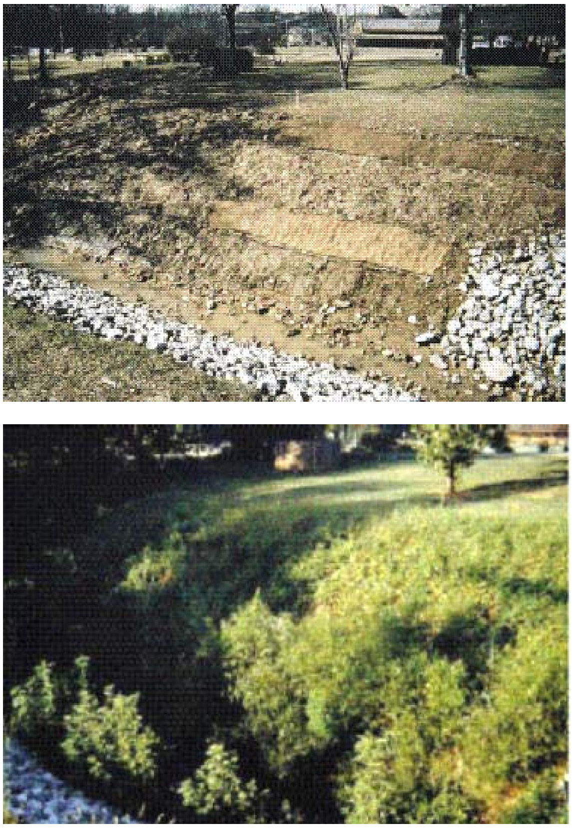


Figure 8.37: A stabilized streambank. *Plant materials can be combined with other materials such as rocks, logs or brush, and natural fabrics. [(a) during and (b) after.]*

Figure 8.38: Eroded bank. *Preliminary site investigation and analyses are critical to successful streambank stabilization design.*

ces and geotechnical failure. The challenge is to recognize which technique matches the strength of protection against the strength of attack and therefore performs most efficiently when tested by the strongest process of erosion and most critical mechanism of failure. Environmental and economic factors are integrated into the selection procedure, generally making soil bioengineering methods very attractive. The chosen solution, however, must first fulfill the requirement of being effective as bank stabilization; otherwise, environmental and economic attributes will be irrelevant.

Soil bioengineering can be a useful tool in controlling streambank erosion, but it should not be considered a panacea. It must be performed in a judicious manner by personnel experienced in channel processes, biology, and streambank stabilization techniques.

Stabilization Techniques

Plants may be established on upper bank and floodplain areas by using traditional techniques for seeding or by planting bare-root and container-grown plants. However, these approaches provide little initial resistance to flows, and plantings may be destroyed if subjected to high water before they are fully established. Cuttings, pole plantings, and live stakes taken from species that sprout readily (e.g., willows) are more resistant to erosion and can be used lower on the bank (**Figure 8.40**). In addition, cuttings and pole plantings can provide immediate moderation of flow velocities if planted at high densities. Often, they can be placed deep enough to maintain contact with adequate soil moisture levels, thereby eliminating the need

CASE STUDY

Careless Creek, Montana

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

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

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

Any remaining willows or other species were eliminated in the following years as ranchers began spraying riparian areas to control sage-brush. This accelerated the streambank erosion as barren, sometimes vertical, banks began sloughing off chunks of salted gnones developed to help the planning effort. Many organizations took part, including the Upper and Lower Musselshell Conservation Districts; Natural Resources Conservation Service; Montana Department of Natural Resources and Conservation; Montana Department of Fish; Wildlife and Parks; Deadman's Basin Water Users Association; U.S. Bureau of Reclamation; Central Montana RC&D; City of Roundup; Roundup Sportsmen; county commissioners; and local landowners.

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

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

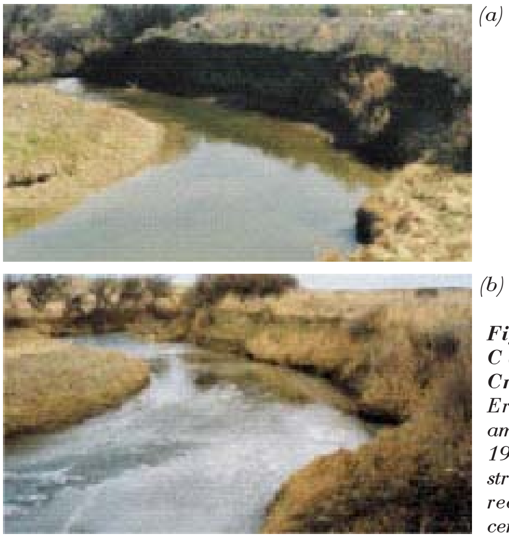


Figure 8.39: Careless Creek. (a) Eroded streambank (May 1995) and (b) streambank in recovery (December 1997).

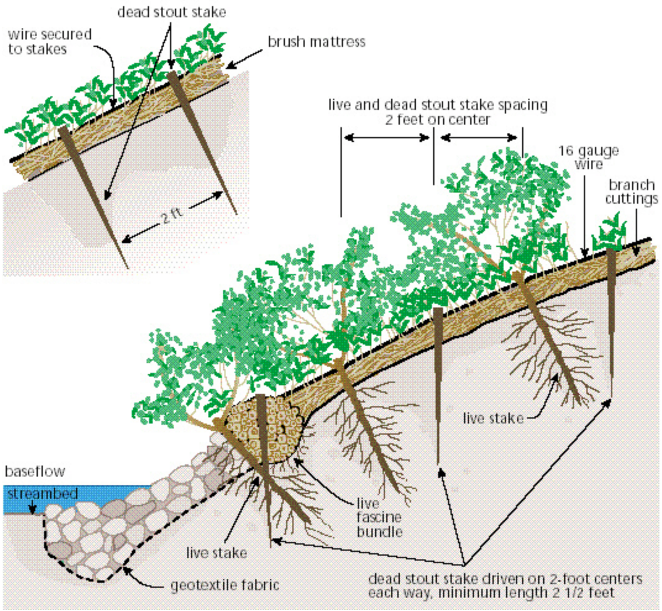


Figure 8.40: Cutting systems. *Details of brushmattress technique.* Source: USDA-NRCS 1996a. *Note: Rooted/leafed condition of the living plant material is not representative at the time of installation.*

Figure 8.41: Results of live staking along a streambank. *Pioneer species are often most appropriate for use in bank revegetation projects.*

for irrigation. The reliable sprouting properties, rapid growth, and general availability of cuttings of willows and other pioneer species makes them particularly appropriate for use in bank revegetation projects, and they are used in most of the integrated bank protection approaches described here (see **Figure 8.41**).

Anchored Cutting Systems

Several techniques are available that employ large numbers of cuttings arranged in layers or bundles, which can be secured to streambanks and partially buried. Depending on how these systems are arranged, they can provide direct protection from erosive flows, prevent erosion from upslope water sources, promote trapping of sediments, and quickly develop dense roots and sprouts. Brush mattresses and woven mats are typically used on the face of a bank and consist of cuttings laid side by side and interwoven or pinned down with jute cord or wire held in place by stakes. Brush layers are cuttings laid on terraces dug into the bank, then buried so that the branch ends extend from the bank. Fascines or wattles are bundles of cuttings tied together, placed in shallow trenches arranged horizontally on the bank face, partially buried, and staked in place. A similar system, called a reed roll, uses partially buried and staked burlap rolls filled with soil and root material or rooted shoots to establish herbaceous species in appropriate habitats. Anchored bundles of live cuttings also have been installed perpendicular to the channel on newly constructed gravel floodplain areas to dissipate floodwater energy and encourage deposition of sediment (Karle and Densmore 1994).

Geotextile Systems

Geotextiles have been used for erosion control on road embankments and other upland settings, usually in combination with seeding, or with plants placed through slits in the fabric. In self-sustaining streambank applications, only natural, biodegradable materials should be used, such as jute or coconut fiber (Johnson and Stypula 1993). The typical streambank use for these materials is in the construction of vegetated geogrids, which are similar to brush layers except that the fill soils between the layers of cuttings are encased in fabric, allowing the bank to be constructed of successive "lifts" of soil, alternating with brush layers. This approach allows reconstruction of a bank and provides considerable erosion resistance (see Green River case study). Natural fibers are also used in "fiber-schines," which are sold specifically for streambank applications. These are cylindrical fiber bundles that can be staked to a bank with cuttings or rooted plants inserted through or into the material.

Vegetated plastic geogrids and other nondegradable materials can also be used where geotechnical problems require drainage or additional strength.

Integrated Systems

A major concern with the use of structural approaches to streambank stabilization is the lack of vegetation in the zone directly adjacent to the water. Despite a long-standing concern that vegetation destabilizes stone revetments, there has been little supporting evidence and even some evidence to the contrary (Shields 1991). Assuming that loss of conveyance is accounted for, the addition of vegetation to structures should be considered. This can involve placement of cuttings during construction, or insertion of cuttings and poles between stones on existing structures. Timber cribwalls may also be constructed with cuttings or rooted plants extending through the timbers from the backfill soils.

Trees and Logs

Tree revetments are made from whole tree trunks laid parallel to the bank, and cabled to piles or deadman anchors. Eastern red cedar (*Juniperus virginiana*) and other coniferous trees are used on small streams, where their springy branches provide interference to flow and trap sediment. The principal objective to these systems is the use of large amounts of cable and the potential for trees to be dislodged and cause downstream damage.

Some projects have successfully used large trees in conjunction with stone to provide bank protection as well as improved aquatic habitat (see case study). Large logs with intact root wads are placed in trenches cut into the bank, such that the root wads extend beyond the bank face at the toe (**Figure 8.42**). The logs are overlapped and/or braced with stone to ensure stability, and the protruding rootwads effectively reduce flow velocities at the toe and over a range of flow elevations (**Figure 8.43**). A major advantage of this approach is that it reestablishes one of the natural roles of large woody debris in streams by creating a dynamic near-bank environment that traps organic material and provides colonization substrates for invertebrates and refuge habitats for fish. The logs eventually rot, resulting in a more natural bank. The revetment stabilizes the bank until woody vegetation has matured, at which time the channel can return to a more natural pattern.

In most cases, bank stabilization projects use combinations of the techniques described above in an integrated approach. Toe protection often requires the use of stone, but amounts can be greatly reduced if large logs can also be used. Likewise, stone blankets on the bank face can be replaced with geogrids or supplemented with interstitial plantings. Most upper bank areas can usually be stabilized using vegetation alone, although anchoring systems might be required. The Green River bank restoration case study illustrates one successful application of an integrated approach on a moderate-sized river in Washington State.

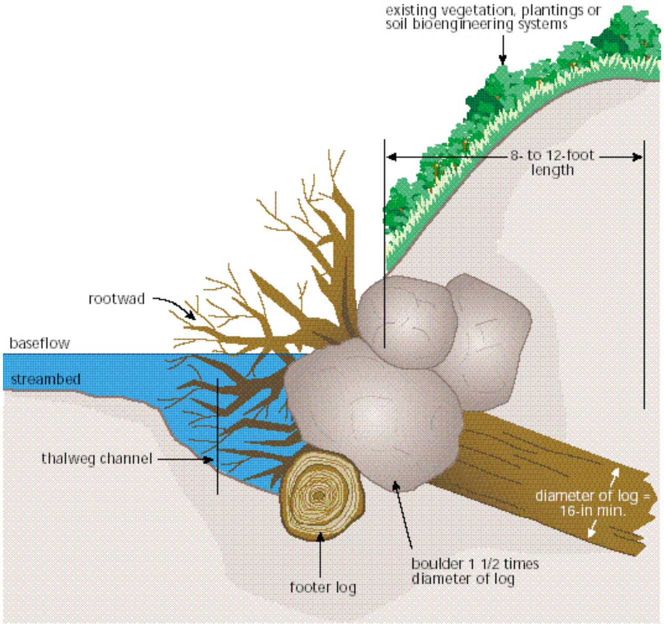


Figure 8.42: Revetment system. *Details of rootwad and boulder technique.*
Source: USDA-NRCS 1996a.

Figure 8.43: Installation of logs with intact root wads. *An advantage to using tree revetments is the creation of habitat for invertebrates and fish along the streambank.*

CASE STUDY

Green River Bank Restoration Initiative

King County, Washington

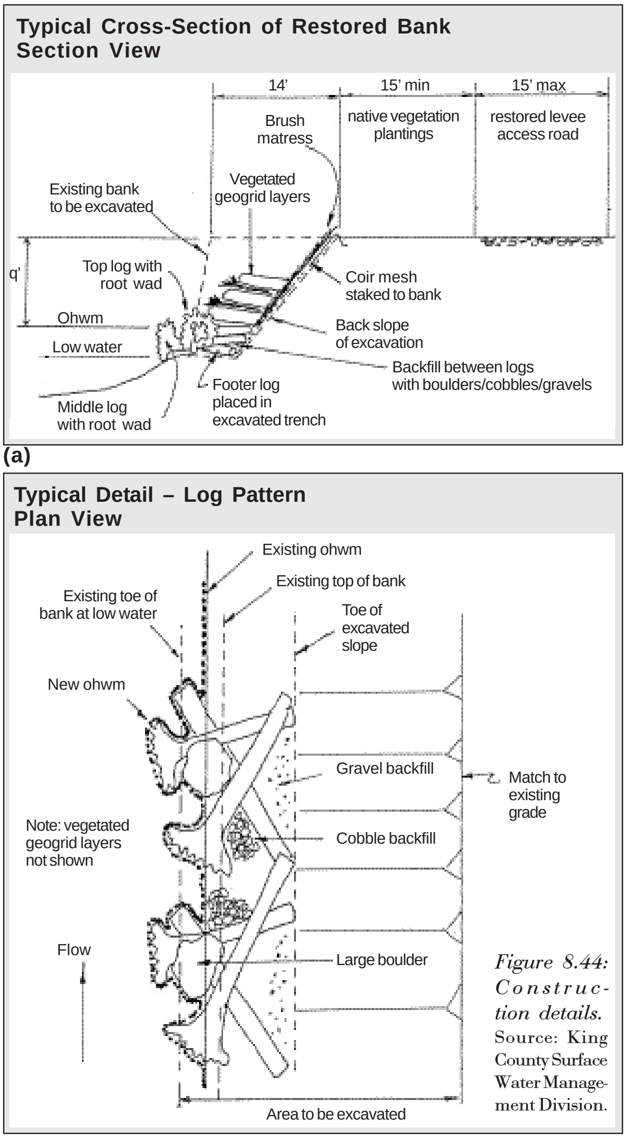
The King County, Washington, Surface Water Management Division initiated a bank restoration initiative in 1994 that illustrates a variety of project objectives and soil bioengineering approaches ***(Figure 8.44)****. The project involved stabilization of the bank of the Green River along a 500-foot section of a meander bend that was rapidly migrating into the adjacent farm field. The project objectives included improvement of fish and wildlife habitat, particularly for salmonids.*

Site investigations included surveys of stream cross sections, velocity measurements at two discharge levels, soil characterizations, and assessment of fish use of existing habitat features in the area. The streambank was vertical, 5 to 10 feet high, and composed of silty-clay-loam alluvium with gravel lenses. Flow velocities were 2 to 5 fps for flows of 200 and 550 cfs. Fish were primarily observed in areas of low velocities and/or near woody debris, and along the channel margins. In August, large woody debris was *installed along the toe of the bank. The logs were cedar and fir, 25 feet long and 28 to 36 inches in diameter, with root wads 6 to 8 feet in diameter. The logs were placed in trenches cut 15 feet back into the bank so that the root wads extended into the channel, and large (3- to 4-foot diameter) boulders were placed among the logs at the toe. Log and boulder placement was designed to interlock and brace the logs and prevent movement. The project used approximately 10 logs and 20 boulders per 100 lineal feet of bank. In September, vegetated geogrids were installed above the toe zone to stabilize the high bank* ***(Figure 8.45)****.*

The project was completed with installation of a variety of plants, including container-grown conifers and understory species, in a minimum 25-foot buffer along the top of the bank. Within 2 months of completion, the site was subjected to three high flows, including an 8,430-cfs event in December 1994. Measured velocities along the bank were less than 2 fps at the surface and less than 1 fps 2 feet below the surface, indicating the effectiveness of the root wads in moderating flow velocities ***(Figure 8.46)****. Some surface erosion and washout of plants along the top bank occurred, and a subsequent event caused minor damage to the geogrid at one location.*

The maintenance repairs consisted of replanting and placement of additional logs to halt undermining of the geogrid. The 1995 growing season produced dramatic growth of the willow cuttings in the geogrid, although many of the planted trees in the overbank zone died ***(Figure 8.47)****. Initial observations have documented extensive fish use of the slow-water habitats among the root wads at the toe of the bank, and in scour holes created by flows deflected toward the channel bottom.*

The site continues to be carefully monitored, and the effectiveness of the approach has led to the implementation of similar designs elsewhere in the region. The project designers have concluded that future projects of this type should use small plants rather than large rooted material in the overbank zone to reduce costs, improve survival, and minimize damage due to equipment access for maintenance or repair. Based on their obsevations of fish response along the restored bank and in nearby stream reaches, they also recommend that future projects incorporate a greater variety of woody debris, including brushy material and tree tops, along the toe and lower bank.



(a)

(b)

Figure 8.44: Construction details. Source: King County Surface Water Management Division.

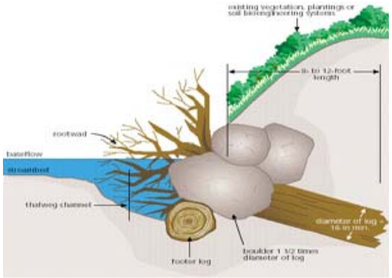


Figure 8.45: Partially installed vegetated geogrid. *Installed above the toe to stabilize high bank.*

Figure 8.46: Completed system. *Note calm water along bankline during high flow.*

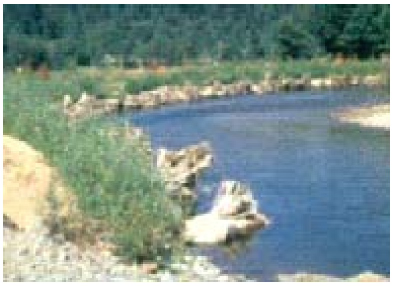


Figure 8.47: Completed system after one year. *Note dramatic willow growth from vegetated geogrid.*

8.G Instream Habitat Recovery

As described in Chapter 2, habitat is the place where a population lives and includes living and nonliving components. For example, fish habitat is a place, or set of places, in which a single fish, a population, or an assemblage of fish can find the physical, chemical, and biological features needed for life, including suitable water quality, passage routes, spawning grounds, feeding and resting sites, and shelter from predators and adverse conditions (**Figure 8.48**). Principal factors controlling the quality of the available aquatic habitat include:

- Streamflow conditions.
- Physical structure of the channel.
- Water quality (e.g., temperature, pH, dissolved oxygen, turbidity, nutrients, alkalinity).
- The riparian zone.
- Other living components.

The existing status of aquatic habitats within the stream corridor should be assessed during the planning stage (Part II). Design of channels, structures, or restoration features can be guided and fine tuned by assessing the quality and quantity of habitats provided by the proposed design. Additional guidance on assessing the quantity and quality of aquatic habitat is provided in Chapter 7.

This section discusses the design of instream habitat structures for the purpose of enhancing physical aquatic habitat quality and quantity. It should be noted, however, that the best approach to habitat recovery is to restore a fully functional, well-vegetated stream corridor within a well-managed watershed. Man-made structures are less sustainable and rarely as effective as a stable channel. Over the long term, design should rely on natural fluvial processes interacting with floodplain vegetation and associated woody debris to provide high-quality aquatic habitat. Structures have little effect on populations that are limited by factors other than physical habitat.

Instream Habitat Features

The following procedures to restore instream habitat are adapted from Newbury and Gaboury (1993) and Garcia (1995).

- Select stream. Give priority to reaches with the greatest difference between actual (low) and potential (high) fish carrying capacity and with a high capacity for natural recovery processes.
- Evaluate fish populations and their habitats. Give priority to reaches with habitats and species of special interest. Is this a biological, chemical, or physical problem? If a physical problem:
- Diagnose physical habitat problems.
  - Drainage basin. Trace watershed lines on topographical and geological maps to identify sample and rehabilitation basins.
  - Profiles. Sketch main stem and tributary long profiles to identify discontinuities that might cause abrupt changes in stream characteristics (falls, former base levels, etc.).
  - Flow. Prepare flow summary for rehabilitation reach using existing or nearby records if available (flood frequency, minimum flows, historical mass curve). Correct for drainage area differences. Compare magnitude and duration of flows during spawning and incubation to year class strength data to determine minimum and maximum flows required for successful reproduction.
  - Channel geometry survey. Select and survey sample reaches to establish the relationship between channel geometry, drainage area, and bankfull channel-forming discharge (**Figure 8.49**). Quantify hydraulic parameters at design discharge.
  - Rehabilitation reach survey. Survey rehabilitation reaches in sufficient detail to prepare channel cross section profiles and construction drawings and to establish survey reference markers.
  - Preferred habitat. Prepare a summary of habitat factors for biologically preferred reaches using regional references and surveys. Identify multiple limiting factors for the species and life stages of greatest concern. Where possible, undertake reach surveys in reference streams with proven populations to identify local flow conditions, substrate, refugia, etc.
- Design a habitat improvement plan. Quantify the desired results in terms of hydraulic changes, habitat improvement, and population increases.
  - Integrate selection and sizing of rehabilitation works with instream flow requirements.
  - Select potential schemes and structures that will be reinforced by the existing stream dynamics and ge-

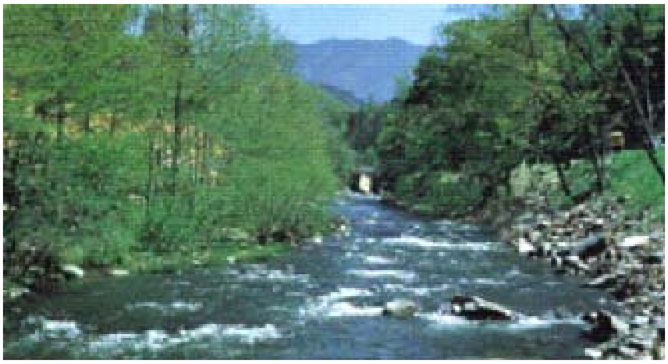


Figure 8.48: Instream habitat. *Suitable water quality, passage routes, and spawning grounds are some of the characteristics of fish habitat.*

Man-made structures are less sustainable and rarely as effective as a stable channel.

Figure 8.49: Surveying a stream. *Channel surveys establish baseline information needed for restoration design.*

ometry. The following section provides additional detail on use of habitat structures.
  - Test designs for minimum and maximum flows and set target flows for critical periods derived from the historical mass curve.
- Implement planned measures.
  - Arrange for on-site location and elevation surveys and provide advice for finishing details in the stream.
- Monitor and evaluate results.
  - Arrange for periodic surveys of the rehabilitated reach and reference reaches, to improve the design, as the channel ages.

Instream Habitat Structures

Aquatic habitat structures (also called instream structures and stream improvement structures) are widely used in stream corridor restoration. Common types include weirs, dikes, random rocks, bank covers, substrate reinstatement, fish passage structures, and off-channel ponds and coves. Institutional factors have favored their use over more holistic approaches to restoration. For example, it is often easier to obtain authority and funding to work within a channel than to influence riparian or watershed land use. Habitat structures have been used more along cold water streams supporting salmonid fisheries than along warm water streams, and the voluminous literature is heavily weighted toward cold water streams.

In a 1995 study entitled Stream Habitat Improvement Evaluation Project, 1,234 structures were evaluated according to their general effectiveness, the habitat quality associated with the given structure type, and actual use of the structures by fish (Bio West 1995). The study determined approximately 18 percent of the structures need maintenance. Where inadequate flows and excessive sediment delivery occur, structures have a brief lifespan and limited value in terms of habitat improvement. Furthermore, the study concluded that instream habitat structures generally provided increased fish habitat.

Before structural habitat features are added to a stream corridor restoration design, project managers should carefully determine whether they address the real need and are appropriate. Major caveats include the following:

- Structures should never be viewed as a substitute for good riparian and upland management.
- Defining the ecological purpose of a structure and site selection are as important as construction technique.
- Scour and deposition are natural stream processes necessary to create fish habitat. Overstabilization therefore limits habitat potential, whereas properly designed and sited structures can speed ecological recovery.
- Use of native materials (stone and wood) is strongly encouraged.
- Periodic maintenance of structures will be necessary and must be incorporated into project planning.

FAST FORWARD

Preview Chapter 9
for an ntroduction to construction and monitoring follow-up activities.

Instream Habitat Structure Design

Design of aquatic habitat structures should proceed following the steps presented below (Shields 1983). However, the process should be viewed as iterative, and considerable recycling among steps should be expected.

- Plan layout.
- Select types of structures.
- Size the structures.
- Investigate hydraulic effects.
- Consider effects on sediment transport.
- Select materials and design structures.

Each step is described below. Construction and monitoring follow-up activities are described in Chapter 9.

Plan Layout

The location of each structure should be selected. Avoid conflicts with bridges, riparian structures, and existing habitat resources (e.g., stands of woody vegetation). The frequency of structures should be based on the habitat requirements previously determined, within the context of the stream morphology and physical characteristics (see Chapter 7). Care should be taken to place structures where they will be in the water during baseflow. Structures should be spaced to avoid large areas of uniform conditions. Structures that create pools should be spaced five to seven channel widths apart. Weirs placed in series should be spaced and sized carefully to avoid placing a weir within the backwater zone of the downstream structure, since this would create a series of pools with no intervening riffles or shallows.

Select Types of Structures

The main types of habitat structures are weirs, dikes (also called jetties, barbs, deflectors (**Figure 8.50**), spurs, etc.), random rocks (also called boulders), and bank covers (also called lunkers). Substrate reinstatement (artificial riffles), fish passage structures, and off-channel ponds and coves have also been widely employed. Fact sheets on several of these techniques are provided in the *Techniques Appendix*, and numerous design web sites are available (White and Brynildson 1967, Seehorn 1985, Wesche 1985, Orsborn et al. 1992, Orth and White 1993, Flosi and Reynolds 1994).

Evidence suggests that traditional design criteria for widespread bank and bed stabilization measures (e.g., concrete grade control structures, homogeneous riprap) can be modified, with no functional loss, to better meet environmental objectives and improve habitat diversity. **Table 8.7** may be used as a general guide to relate structural type to habitat requirement. Weirs are generally more failure-prone than deflectors. Deflectors and random rocks are minimally effective in environments where higher flows do not produce sufficient local velocities to produce scour holes near structures. Random rocks (boulders) are especially susceptible to undermining and burial when placed in sand-bed channels, although all types of stone structures experience similar problems. Additional guidance for evaluating the general suitability of various fish habitat structures for a wide range of morphological stream types is provided by Rosgen (1996). Seehorn (1985) provides guidance for small streams in the eastern United States. The use of any of these guides should also consider the relative stability of the stream, including aggradation and incision trends, for final design.

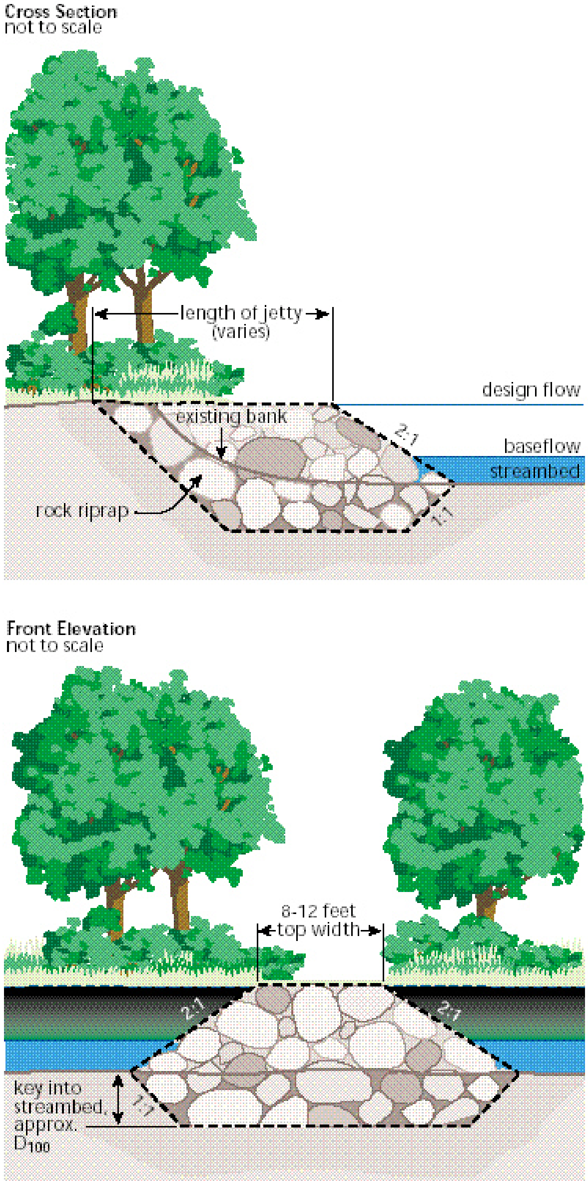


Figure 8.50: Instream habitat structure. *Wing deflector habitat structure.*
Source: USDA-NRCS 1996a.

Size the Structures

Structures should be sized to produce the desired aquatic habitats at the normal range of flows from baseflow to bankfull discharge. A hydrological analysis can provide an estimate of the normal range of flows (e.g., a flow duration curve), as well as an estimate of extreme high and low flows that might be expected at the site (see Chapter 7). In general, structures should be low enough that their effects on the water surface profile will be slight at bankfull discharge. Detailed guidance by structural type is presented in the Techniques Appendix. For informal design, empirical equations like those presented by Heiner (1991) can be used to roughly estimate the depth of scour holes at weirs and dikes.

Investigate Hydraulic Effects

Hydraulic conditions at the design flow should provide the desired habitat; however, performance should also be evaluated at higher and lower flows. Barriers to movement, such as extremely shallow reaches or vertical drops not submerged at higher flows, should be avoided. If the conveyance of the channel is an issue, the effect of the proposed structures on stages at high flow should be investigated. Structures may be included in a standard backwater calculation model as contractions, low weirs, or increased flow resistance (Manning) coefficients, but the amount of increase is a matter of judgment or limited by National Flood Insurance Program ordinances. Scour holes should be included in the channel geometry downstream of weirs and dike since a major portion of the head loss occurs in the scour hole. Hydraulic analysis should include estimation or computation of velocities or shear stresses to be experienced by the structure.

Consider Effects on Sediment Transport

If the hydraulic analysis indicates a shift in the stage-discharge relationship, the sediment rating curve of the restored reach may change also, leading to deposition or erosion. Although modeling analyses are usually not cost-effective for a habitat structure design effort, informal analyses based on assumed relationships between velocity and sediment discharge at the bankfull discharge may be helpful in detecting potential problems. An effort should be made to predict the locations and magnitude of local scour and deposition. Areas projected to experience significant scour and deposition should be prime sites for visual monitoring after construction.

Select Materials

Materials used for aquatic habitat structures include stone, fencing wire, posts, and felled trees. Priority should be given to materials that occur on site under natural conditions. In some cases, it may be possible to salvage rock or logs generated from construction of channels or other project features.

Logs give long service if continuously submerged. Even logs not continuously wet can give several decades of service if chosen from decay-resistant species. Logs and timbers must be firmly fastened together with bolts or rebar and must be well anchored to banks and bed. Stone size should be selected based on design velocities or shear stress.

Table 8.7: Fish habitat improvement structures–suitability for stream types. Source: Rosgen 1996.

Channel Type	Low St. Check Dam	Medium St. Check Dam	Boulder Placement	Bank Boulder Placement	Single Wing Deflector	Double Wing Deflector	Channel Constrictor	Bank Cover
A1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B1-1	Poor	Poor	Good	Excellent	Poor	Poor	Poor	Good
B1	Excellent	Excellent	N/A	N/A	Excellent	Excellent	N/A	Excellent
B2	Excellent	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
B3	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
B4	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
B5	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
C1-1	Poor	Poor	Fair	Excellent	Poor	Poor	Poor	Good
C1	Good	Fair	Fair	Excellent	Good	Good	Fair	Good
C2	Excellent	Good	Good	Excellent	Good	Excellent	Excellent	Good
C3	Fair	Poor	Poor	Good	Fair	Fair	Fair	Good
C4	Fair	Poor	Poor	Good	Poor	Poor	Poor	Fair
C5	Fair	Poor	Poor	Good	Poor	Poor	Poor	Poor
C6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D1	Fair	Poor	Poor	Fair	Fair	Fair	Fair	Poor
D2	Fair	Poor	Poor	Fair	Fair	Fair	Fair	Poor

Channel Type	Half Log Cover	Floating Log Cover	Submerged Shelter		Migration Barrier	Gravel Traps		Gravel Placement
			Meander	Straight		"V" Shaped	Log	
A1	N/A	N/A	N/A	N/A	Excellent	Good	Poor	Poor
A2	N/A	N/A	N/A	N/A	Excellent	Excellent	Excellent	Poor
B1-1	Good	Good	Good	Excellent	Fair	Good	Good	Fair
B1	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair
B2	Excellent	Excellent	Good	Excellent	Good	Good	Good	Good
B3	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
B4	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
B5	Poor	Fair	Fair	Fair	Poor	Poor	Poor	Poor
C1-1	Good	Good	Good	Excellent	Poor	Fair	Fair	Fair
C1	Good	Good	Good	Excellent	Poor	Fair	Good	Fair
C2	Good	Excellent	Excellent	Excellent	Poor	Good	Excellent	Excellent
C3	Fair	Good	Fair	Good	Poor	N/A	N/A	N/A
C4	Poor	Good	Fair	Good	Poor	Poor	Poor	Poor
C5	Poor	Good	Fair	Good	Poor	Poor	Poor	Poor
C6	N/A	N/A	N/A	N/A	Poor	Poor	Fair	Fair
D1	Poor	Poor	Poor	Poor	Poor	Poor	N/A	Poor
D2	Poor	Poor	Poor	Poor	Poor	N/A	Poor	Poor

Key:
Excellent - No limitation to location of structure placement or special modification in design.
Good - Under most conditions, very effective. Minor modification of design or placement required.
Fair - Serious limitation which can be overcome by placement location, design modification, or stabilization techniques.
Generally not recommended due to difficulty of offsetting potential adverse consequences and high probability of reduced effectiveness.
Poor - Not recommended due to morphological character of stream type and very low probability of success.
Not Applicable - Generally not considered since habitat components are not limiting.
Note : A3, A3-a, A4, A4-a, A5, A5-a channel types are not evaluated due to limited fisheries value.

8.H Land Use Scenarios

As discussed in Chapter 3, most stream corridor degradation is directly attributable to land use practices and/ or hydrologic modifications at the watershed level that cause fundamental disruption of ecosystem functions (Beschta et al. 1994) (**Figure 8.51**). Ironically, land use practices, including hydrologic modifications, can offer the opportunity for restoring these same degraded stream corridors. Where feasible, the objective of the restoration design should be to eliminate or moderate disruptive influences sufficiently to allow recovery of dynamic equilibrium over time (NRC 1992).

If chronic land use impacts on the stream or riparian system cannot be controlled or moderated, or if some elements of the stream network (e.g., headwaters) are not included in the restoration design, it must be recognized that the restoration action may have limited effectiveness in the long-term.

Restoration measures can be designed to address particular, site-specific deficiencies (an eroding bank, habitat features), but if they do not restore self-maintaining processes and the functions of a stream corridor, they must be regarded as a focused "fix" rather than an ecosystem restoration. In cases where land use practices are the direct cause of stream corridor degradation and there is a continuing downward trend in landscape condition, there is little point in expending resources to address symptoms of the problem rather than the problem itself (DeBano and Schmidt 1989).

Design Approaches for Common Effects

Figure 8.51: Sediment-laden stream. *Most stream corridor degradation can be attributed to impacts resulting from surrounding land uses.*

Agriculture, forestry, grazing, mining, recreation, and urbanization are some of the principal land uses that can result in disturbance of stream corridor structure and functions. A watershed analysis will help prioritize and coordinate restoration actions (Platts and Rinne 1985, Swanson 1989) and may indicate critical or chronic land use activities causing disturbance both inside and outside the stream corridor. Addressing these in the restoration plan and design, may greatly improve the effectiveness and success of restoration work.

Restoration measures designed in response to these effects may be similar across land uses. Sediment and nutrient management in urban, agricultural, and forest settings, for instance, may require the use of buffer strips. Although the buffer strips have many common design characteristics, each setting has site-specific factors.

Dams

Dams alter the flow of water, sediment, organic matter, and nutrients, resulting in both direct physical and indirect biological effects in tailwaters and downstream riparian and floodplain areas (see Chapter 3). Stream corridors below dams can be partially restored by modifying operation and management approaches. Impacts from the operation of dams on surface water quality and aquatic and riparian habitat should be assessed and the potential for improvement evaluated. The modification of operation approaches, where possible, in combination with the application of properly designed and applied best management practices, can reduce the impacts caused by dams on downstream riparian and floodplain habitats.

Best management practices can be applied individually or in combination to protect and improve surface water quality and aquatic habitat in reservoirs as well as downstream. Several approaches have been designed for improving or maintaining acceptable levels of dissolved oxygen (DO), temperature, and other constituents in reservoirs and tailwaters. One design approach uses pumps, air diffusers, or air lifts to induce circulation and mixing of the oxygen-poor but cold hypolimnion with the oxygen-rich but warm epilimnion, resulting in a more thermally uniform reservoir with increased DO. Another design approach for improving water quality in tailwaters for trout fisheries involves mixing of air or oxygen with water passing through the turbines at hydropower dams to improve concentrations of DO. Reservoir waters can also be aerated by venting turbines to the atmosphere or by injecting compressed air into the turbine chamber (USEPA 1993).

Modification to the intakes, the spillway, or the tailrace of a dam can also be designed to improve temperature or DO levels in tailwaters. Installing various types of weirs downstream of a dam achieves similar results. These design practices rely on agitation and turbulence to mix reservoir releases with atmospheric air to increase levels of DO (USEPA 1993).

Adequate fish passage around dams, diversions, and other obstructions may be a critically important component of restoring healthy fish populations to previously degraded rivers and streams. A fact sheet in Appendix A shows an example for fish passages. However, designing, installing, and operating fish passage facilities at dams are beyond the scope of this handbook. Further, the type of fish passage facility and the flows necessary for operation are generally site specific. Further information on fish passage technology can be found in other references, including Environmental Mitigation at Hydroelectric Projects - Volume II. Benefits and Costs of Fish Passage and Protection (Francfort et al., 1994); and Fish Passage Technologies: Protection at Hydropower Facilities (Office of Technology Assessment, Congress of the United States, Washington DC, OTA-ENV-641).

Adjusting operation procedures at some dams can also result in improved quality of reservoir releases and downstream conditions. Partial restoration of stream corridors below dams can be achieved by designing operation procedures that mimic the natural hydrograph, or desirable aspects of the hydrograph. Modifications include scheduling releases or the duration of shutoff periods, instituting procedures for the maintenance of minimum flows, and making seasonal adjustments in pool levels and in the timing and variation of the rates of drawdowns (USEPA 1993).

Modifying operation and management approaches, in combination with the application of properly designed best management practices, can be an effective approach to partially restoring stream corridors below dams. However, dam removal is the only way to begin to fully restore a stream to its natural condition. It is important to note, however, that unless accomplished very carefully, with sufficient studies and modeling and at significant cost, removing a dam can cause more damage downstream (and upstream) than the dam is currently causing until a state of dynamic equilibrium is reached. Dam removal lowers the base level of upstream tributaries, which can cause rejuvenation, bed and bank instability, and increased sediment loads. Dam removal can also result in the loss of wetlands and habitat in the reservoir and tributary deltas.

Three options should be considered— complete removal, partial removal, and staged breaching. The option is selected based on the condition of the dam and future maintenance required if not completely removed, and on the best way to deal with the sediment now stored behind the dam. The following elements must be considered in managing sediment:

- Removing features of dams necessary to restore fish passage and ensure safety.
- Revegetation of the reservoir areas.
- Long-term monitoring of sediment transport and river channel topography, water quality, and aquatic ecology.
- Long-term protection of municipal and industrial water supplies.
- Mitigation of flood impacts caused by long-term river aggradation.
- Quality of sediment, including identification of the lateral and vertical occurrence of toxic or otherwise poor-quality sediment.

Water quality issues are primarily related to suspended sediment concentration and turbidity. These are important to municipal, industrial, and private water users, as well as to aquatic communities. Water quality will primarily be affected by any silt and clay released from the reservoirs and by reestablishment of the natural sediment loads downstream. During removal of the dam and draining of the lake, the unvegetated reservoir bottoms will be exposed. Lakebeds will be expected to have large woody debris and other organic material. A revegetation program is necessary to control dust, surface runoff, and erosion and to restore habitat and aesthetic values. A comprehensive sediment management plan is needed to address the following:

- Sediment volume and physical properties.
- Sediment quality and associated disposal requirements.
- Hydraulic and biological characteristics of the reservoir and downstream channel.
- Alternative measures for sediment management.
- Impacts on downstream environment and channel hydraulics.
- Recommended measures to manage sediment properly and economically.

Objectives of sediment management should include flood control, water quality, wetlands, fisheries, habitat, and riparian rights.

For hydropower dams, the simplest decommissioning program is to dismantle the turbine-generator and seal the water passages, leaving the dam and water-retaining structures in place. No action is taken concerning the sediments since they will remain in the reservoir and the hydraulic and physical characteristics of the river and reservoir will remain essentially unchanged. This approach is viable only if there are no deficiencies in the water-retaining structures (such as inadequate spillway capacity or inadequate factors of safety for stability) and long-term maintenance is ensured. In some cases, decommissioning can include partial removal of water-retaining structures. Partial removal involves demolition of a portion of the dam to create a breach so that it no longer functions as a water-retaining structure.

For additional information, see Guidelines for the Retirement of Hydroelectric Facilities published by the American Society of Civil Engineers (ASCE) in 1997.

Channelization and Diversions

Channelization and flow diversions represent forms of hydrologic modification commonly associated with most principal land uses, and their effects should be considered in all restoration efforts (see Chapter 3). In some cases, restoration design can include the removal or redesign of channel modifications to restore preexisting ecological and flow characteristics.

Modifications of existing projects, including operation and maintenance or management, can improve some negative effects without changing the existing benefits or creating additional problems. Levees may be set back from the stream channel to better define the stream corridor and reestablish some or all of the natural floodplain functions. Setback levees can be constructed to allow for overbank flooding, which provides surface water contact with stream-side areas such as floodplains and wetlands.

Instream modifications such as uniform cross sections or armoring associated with channelization or flow diversions may be removed, and design and placement of meanders can be

CASE STUDY

The Multispecies Riparian Buffer System in the Bear Creek, IA Watershed

Introduction

The Bear Creek Watershed in central Iowa is a small (26.8 mi^2) drainage basin located within the Des Moines Lobe subregion of the Western Corn Belt Plains ecoregion, one of the youngest and flattest ecological subregions in Iowa. In general, the land is level to gently rolling with a poorly developed stream network. Soils of the region are primarily developed in glacial till and alluvial, lacustrine, and windblown deposits. Prior to European settlement of the region (ca 1847) the watershed consisted of the vast tallgrass prairie ecosystem, interspersed with wet prairie marshes in topographic lows and gallery forests along larger order streams and rivers. Native forest was limited to the Skunk River corridor into which Bear Creek flows.

Subsequent conversion of the land, including the riparian zone, from native vegetation to row crops, extensive subsurface drainage tile installation, dredge ditching, and grazing of fenced riparian zones have resulted in substantial stream channel modification. Records suggest that artificial drainage of marshes and low prairies in the upper reaches of the Bear Creek watershed was completed about 1902, with ditch dredging completed shortly thereafter. While the main stream pattern appears to have remained about the same since that time, significant channelization continued into the 1970s. Additional intermittent channels have developed in association with new drainage tile and grass waterway installation. Present land use in the Bear Creek watershed is typical of the region, with over 87% of the land area devoted to row crop agriculture.

Landscape modifications and present land-use practices have produced nonpoint source pollution in the watershed, which landowners have addressed by implementing soil conservation practices (e.g. reduced tillage, terracing, grass waterways) and better chemical input management (e.g. more accurate and better timed applications). It has only been recently that placement or enhancement of riparian vegetation or “streamside filter strips” has been recommended to reduce sediment and chemical loading, modify flow regime by reducing discharge extremes, improve structural habitat, and restore energy relationships through the addition of organic matter and reduction in temperature and dissolved oxygen extremes.

The Riparian Management System (RiMS)

The Agroecology Issue Team of the Leopold Center for Sustainable Agriculture, Iowa State University, Ames, IA, is conducting research on the design and establishment of an integrated riparian management system (RiMS) to demonstrate the benefits of properly functioning riparian buffers in the heavily row-cropped landscape of the midwestern U.S. The purpose of the RiMS is to restore the essential ecological functions that riparian ecosystems once provided. Specific objectives of such buffers are to intercept eroding soil and agricultural chemicals from adjacent crop fields, slow floodwaters, stabilize streambanks, provide wildlife habitat, and improve the biological integrity of aquatic ecosystems. The regionalization of this system has been accomplished by designing it with several components, each of which can be modified to fit local landscape conditions and landowner objectives.

The Agroecology Issue Team is conducting detailed studies of important biological and physical processes at both the field and watershed scale to provide the necessary data to allow resource managers to make credible recommendations of buffer placement and design in a wide variety of landscapes. In addition, socioeconomic data collected from landowners in the watershed are being used to identify landowner criteria for accepting RiMS. The team also is quantifying the non-market value placed on the improvement in surface and ground water quality.

The actual development and establishment of the RiMS along Bear Creek was initiated in 1990 along a 0.6-mile length of Bear Creek on the Ron and Sandy Risdal Farm. The buffer strip system has subsequently been planted along 3.5 miles of Bear Creek upstream from this original site. The RiMS consists of three components: 1) a multispecies riparian buffer (MRB), 2) soil bioengineering technologies for streambank stabilization, and 3) constructed wetlands to intercept and process nonpoint source pollutants in agricultural drainage tile water.

Multi-species Riparian Buffer (MRB)

The general MRB consists of three zones. The rapid growth of this buffer community can change a heavily impacted riparian zone into a functioning riparian ecosystem in a few short years. The combinations of trees, shrubs, and native grasses can be modified to fit site conditions (e.g. soils, slope), major buffer biological and physical function(s), owner objectives, and cost-share program requirements.

Soil Bioengineering

It has been estimated that greater than 50% of the stream sediment load in small watersheds in the Midwest is the result of channel erosion. This problem has been worsened by the increased erosive power of streams resulting from stream channelization and loss of riparian vegetation. Several different soil bioengineering techniques have been employed in the Bear Creek watershed. These include the use of willow posts and stakes driven into the bank, live willow fascines, live willow brush mattresses, and biodegradable geotextile anchored with willow stakes on bare slopes. Alternatives used to stabilize the base of the streambank include rock and anchored dead plant material such as cedar or bundled maple.

Constructed Wetlands

Small, constructed wetlands which are integrated into the riparian buffer have considerable potential to remove nitrate and other chemicals from the extensive network of drain tile in the Midwest. To demonstrate this technology, a small (600^{yd2}) wetland was constructed to process drainage tile water from a 12-acre cropped field. The wetland was constructed by excavating a depressional area near the creek and constructing a low berm. The subsurface drainage tile was rerouted to enter the wetland at a point that maximizes residence time of drainage tile water within the wetland. A simple gated water level control structure at the wetland outlet provides control of the water level maintained within the wetland. Cattail rhizomes (Typha glauca Godr.) collected from a local marsh and road ditch were planted within the wetland and native grasses and forbs planted on the constructed berm. Future plans include the construction of additional tile drainage wetlands within the Bear Creek watershed.

System Effectiveness

Long-term monitoring has demonstrated the significant capability of the RiMS to intercept eroding soil from adjacent cropland, intercept and process agricultural chemicals moving in shallow subsurface water, stabilize stream channel movement, and improve instream environments, while also providing wildlife habitat and quality timber products. The buffer traps 70-80% of the sediment carried in surface runoff and has reduced nitrate and atrazine moving in the soil solution to levels well below the maximum contaminant levels specified by the USEPA. Streambank bioengineering systems have virtually stopped bank erosion along treated reaches and are now trapping channel sediment. The constructed wetland has reduced nitrate in the tile drainage water by as much as 80% depending on the season of the year. Wildlife benefits have also appeared in a very short time, with a nearly fivefold increase in bird species diversity observed within the buffer strip versus an adjacent, unprotected stream reach.

While the RiMS function is being assessed through experimental plot work with intensive process monitoring, economic benefits and costs to landowners and society also are being determined. Landowners surveys, focus groups, and one-on-one interviews have identified the concern that water quality should be improved by reducing chemical and sediment inputs by as much as 50%. Landowners are willing to pay for this improved water quality as well as volunteer their time to help initiate the improvements.

While the RiMS can effectively intercept and treat nonpoint source pollution from the uplands, it should be stressed that a riparian management system cannot replace upland conservation practices. In a properly functioning agricultural landscape, both upland conservation practices and an integrated riparian system contribute to achieving environmental goals and improved ecosystem functioning.

Support for this work is from the Leopold Center for Sustainable Agriculture, the Iowa Department of Natural Resources through a grant from the USEPA under the Federal Nonpoint Source Management Program (Section 319 of the Clean Water Act), and the USDA (Cooperative State Research Education and Extension Service), National Research Initiative Competitive Grants Program, and the Agriculture in Concert with the Environment Program.

used to reestablish more natural channel characteristics. In many cases, however, existing land uses might limit or prevent the removal of existing channel or floodplain modifications. In such cases, restoration design must consider the effects of existing channel modifications or flow diversions, in the corridor and the watershed.

Exotic Species

Exotic species are another common problem of stream corridor restoration and management. Some land uses have actually introduced exotics that have become uncontrolled, while others have merely created an opportunity for such exotics to spread. Again, control of exotic species has some common aspects across land uses, but design approaches are different for each land use.

Control of exotics in some situations can be extremely difficult and may be impractical if large acreages or well-established populations are involved. Use of herbicides may be tightly regulated or precluded in many wetland and streamside environments, and for some exotic species there are no effective control measures that can be easily implemented over large areas (Rieger and Kreager 1990). Where aggressive exotics are present, every effort should be made to avoid unnecessary soil disturbance or disruption of intact native vegetation, and newly established populations of exotics should be eradicated.

Nonnative species such as salt cedar (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) can outcompete native plantings and negatively affect their establishment and growth. The likelihood of successful reestablishment often increases when artificial flows created by impoundments are altered to favor native species and when exotics such as salt cedar are removed before revegetation is attempted (Briggs et al. 1994).

Salt cedar is an aggressive, exotic colonizer in the West due to its long period and high rate of seed production, as well as its ability to withstand long periods of inundation. Salt cedar can be controlled either by clearing with a bulldozer or by direct application of herbicide (Sudbrock 1993); however, improper treatments may actually increase the density of salt cedar (Neill 1990).

Controlling exotics and weeds

can be important because of potential competition with established native vegetation, colonized vegetation, and artificially planted vegetation in restoration work. Exotics compete for moisture, nutrients, sunlight, and space and can adversely influence establishment rates of new plantings. To improve the effectiveness of revegetation work, exotic vegetation should be cleared prior to planting; nonnative growth must also be controlled after planting. General techniques for control of exotics and weeds are mechanical (e.g., scalping or tilling), chemical (herbicides), and fire. For a review of treatment methods and equipment, see U.S. Forest Service (1965) and Yoakum et al. (1980).

Agriculture

America's Private Land—A Geography of Hope (USDA-NRCS 1996b) challenges all of us to "regain our sense of place and renew our commitment to private landowners and the public." It suggests that as we learn more about the complexity of our environment, harmony with ecological processes that extend across all landscapes becomes more of an imperative than an ideal. Furthermore, conservation provisions of the 1996 Farm Bill and accompanying endeavors such as the National Conservation Buffer Initiative (USDA-NRCS 1997) offer flexibility to care for the land as never before. The following land use scenario attempts to express this flexibility in the context of comprehensive, locally led conservation work, including stream corridor restoration.

This scenario offers a brief glimpse into a hypothetical agricultural setting where the potential results of stream corridor restoration might begin to take form. Computer-generated simulations are used to graphically illustrate potential changes brought about by restoration work and associated comprehensive, on-farm conservation planning. It focuses, conceptually, on vegetative clearing, instream modifications, soil exposure and compaction, irrigation and drainage, and sediment or contaminants as the most disruptive activities associated with agricultural land use. Although an agricultural landscape typical of the Midwest was selected for illustrative purposes, the concepts shown can apply in different agricultural settings.

Hypothetical Existing Conditions

Reminiscent of the highly disruptive agricultural activities discussed in Chapter 3, **Figure 8.52** illustrates hypothetical conditions that focus primarily on production agriculture. Although functionally isolated contour terraces and a waterway have been installed in the nearby cropland, the scene depicts an ecologically deprived landscape. Many of the potential disturbance activities and subsequent changes outlined in Chapter 3 come to mind.

Those hypothetically reflected in the figure are highlighted in **Table 8.8**.

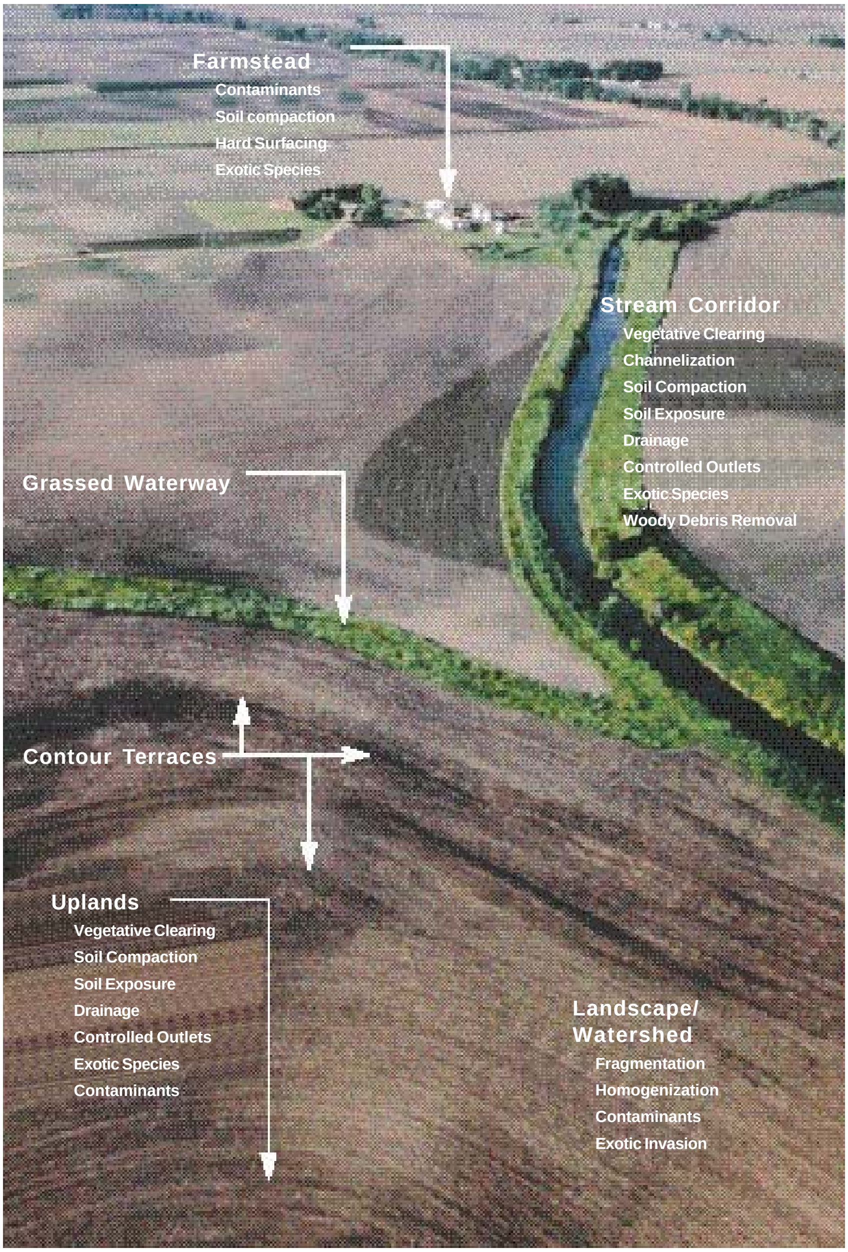


Figure 8.52: Hypothetical conditions. *Activities causing change in this agricultural setting.*

Hypothetical Restoration Response

Previous sections of this chapter and earlier chapters identified connectivity and dimension (width) as important structural attributes of stream corridors. Nutrient and water flow, sediment trapping during floods, water storage, movement of flora and fauna, species diversity, interior habitat conditions, and provision of organic materials to aquatic communities were described as just a few of the functional conditions affected by these structural attributes. Continuous indigenous vegetative cover across the widest possible stream corridor was generally identified as the most conducive to serving the broadest range of functions. This discussion went on to suggest that a long, wide stream corridor with contiguous vegetative cover is a favored overall characteristic. A contiguous, wide stream corridor may be unachievable, however, where competing land uses prevail. Furthermore, gaps caused by disturbances (utility crossings, highways and access lanes, floods, wind, fire, etc.) are commonplace.

Restoration design should establish functional connections within and external to stream corridors. Landscape elements such as remnant patches of riparian vegetation, prairie, or forest exhibiting diverse or unique vegetative communities; productive land that can support ecological functions; reserve or abandoned land; associated wetlands or meadows; neighboring springs and stream systems; ecologically innovative residential areas; and movement corridors for flora and fauna (field borders, windbreaks, waterways, grassed terraces, etc.) offer opportunities to establish these connections. An edge (transition zone) that gradually changes from one land use into another will soften environmental gradients and minimize disturbance.

With these and the broad design guidelines presented in previous sections of this chapter in mind, **Figure 8.53** presents a conceptual computer-generated illustration of hypothetical restoration results. **Table 8.9** identifies some of the restoration measures hypothetically implemented and their potential effects on restoring conditions within the stream corridor and surrounding landscape.

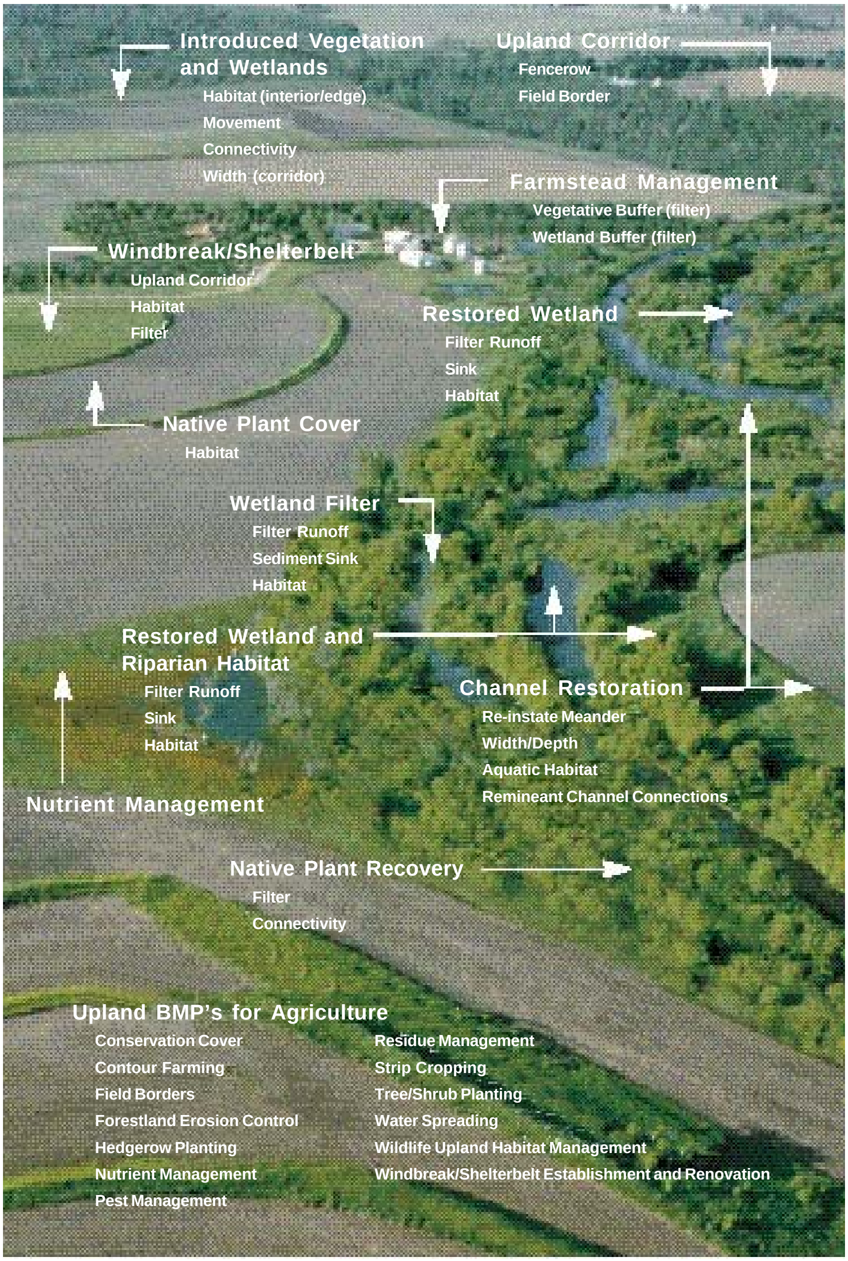


Figure 8.53: Hypothetical restoration response. *Possible results of stream corridor restoration are presented in this computer-altered photograph.*

Forestry

Stream corridors are a source of large volumes of timber. Timber harvesting and related forest management practices in riparian corridors often necessitate stream corridor restoration. Forest management may be an on-going land use and part of the restoration effort. Regardless, accessing and harvesting timber affects streams in many ways including:

- Alteration of soil conditions.
- Removal of the forest canopy.
- Reduction in the potential supply of large organic (woody) debris (Belt et al. 1992).

Table 8.8: Summary of prominent agriculturally related disturbance activities and potential effects.

	Existing Disturbance Activities						
Potential Effects	**Vegetative Clearing**	**Channelization**	**Streambed Disturbance**	**Soil Exposure or Compaction**	**Contaminants**	**Woody Debris Removal**	**Piped Discharge/ Cont. Outlets**
Decreased landscape diversity	■	■	❍	❍	❍	❍	❍
Point source pollution	❍	❍	❍	❍	■	❍	■
Nonpoint source pollution	■	■	■	❍	■	■	■
Dense compacted soil	■	❍	❍	■	❍	❍	❍
Increased upland surface runoff	■	❍	❍	■	❍	❍	❍
Increased sheetflow with surface erosion rill and gully flow	■	❍	❍	■	❍	❍	❍
Increased levels of fine sediment and contaminants in stream corridor	■	■	■	■	■	■	■
Increased soil salinity	❍	❍	❍	❍	■	❍	❍
Increased peak flood elevation	■	■	❍	■	❍	■	■
Increased flood energy	■	■	■	■	❍	■	■
Decreased infiltration of surface runoff	■	❍	❍	■	❍	❍	■
Decreased interflow and subsurface flow to and within the stream corridor	■	■	❍	■	■	❍	■
Reduced ground water recharge and aquifer volumes	■	❍	❍	■	❍	❍	■
Increased depth to ground water	■	■	❍	■	❍	❍	❍
Decreased ground water inflow to stream	■	■	❍	■	❍	❍	■
Increased flow velocities	■	■	■	■	❍	■	■
Reduced stream meander	❍	■	■	❍	❍	■	■
Increased or decreased stream stability	■	■	■	❍	❍	■	■
Increased stream migration	■	❍	■	❍	❍	■	■
Channel widening and downcutting	■	■	■	❍	❍	■	■
Increased stream gradient and reduced energy dissipation	❍	■	■	❍	❍	■	■
Increased flow frequency	■	❍	❍	■	❍	❍	■
Reduced flow duration	■	■	■	■	❍	■	■
Decreased capacity of floodplain and upland	■	❍	❍	■	■	❍	■
Increased sediment and contaminants	■	❍	❍	■	■	■	■
Decreased capacity of stream	❍	■	■	❍	■	■	■
Reduced stream capacity to assimilate nutrients/pesticides	■	■	■	■	■	■	■
Confined stream channel with little opportunity for habitat development	❍	■	■	❍	❍	❍	❍
Increased streambank erosion and channel scour	■	■	■	■	❍	■	■
Increased bank failure	■	■	❍	■	❍	■	■
Loss of instream organic matter and related decomposition	■	■	■	❍	❍	■	■
Increased instream sediment, salinity, or turbidity	■	■	■	❍	■	■	■
Increased instream nutrient enrichment, sedimentation, and contaminants leading to eutrophication	■	❍	■	■	■	■	■
Highly fragmented stream corridor with reduced linear distribution of habitat and edge effect	■	■	❍	❍	❍	■	❍
Loss of edge and interior habitat	■	■	■	❍	❍	■	❍
Decreased connectivity and dimension (width) within corridor and to associated ecosystems	■	■	■	❍	❍	❍	❍
Decreased movement of flora and fauna species for seasonal migration, dispersal repopulation	■	■	■	❍	❍	❍	❍
Reduced stream capacity to assimilate nutrients/pesticides	■	■	■	■	■	■	■
Increase of opportunistic species, predators	■	■	❍	❍	■	■	■
Increased exposure to solar radiation, weather, and temperature	■	■	■	■	❍	■	❍
Magnified temperature and moisture extremes in corridor	■	■	❍	■	❍	❍	❍
Loss of riparian vegetation	■	■	■	■	❍	■	■
Decreased source of instream shade, detritus, food, and cover	■	■	■	❍	❍	❍	■
Loss of edge diversity	■	■	❍	❍	❍	❍	❍
Increased water temperature	■	■	■	❍	❍	❍	■
Impaired aquatic habitat	■	■	■	❍	■	❍	■
Reduced invertebrate population	■	■	■	❍	■	❍	■
Loss of wetland function	❍	■	■	❍	❍	❍	❍
Reduced instream oxygen	❍	■	■	❍	■	❍	■

■ Activity has potential for direct impact

❍ Activity has potential for indirect impact

Table 8.9: Summary of prominent restoration measures and potential resulting effects.

	Restoration Measures						
Potential Resulting Effects	**Wetlands**	**Riparian Habitat**	**Upland Corridors**	**Windbreaks/ Shelterbelts**	**Native Plant Cover**	**Stream Channel Restoration**	**Upland BMPs for Agriculture**
Increased landscape diversity	■	■	■	■	■	■	■
Increased stream order	❍	❍	❍	❍	❍	■	❍
Reduced point source pollution	■	❍	❍	❍	❍	❍	❍
Reduced nonpoint source pollution	■	■	■	■	■	■	■
Increased soil friability	❍	❍	❍	❍	■	❍	■
Decreased upland surface runoff	❍	❍	❍	■	■	❍	■
Decreased sheetflow, width, surface erosion, rill and gully flow	❍	■	❍	❍	■	❍	■
Decreased levels of fine sediment and contaminants in stream corridor	■	■	■	■	■	❍	■
Decreased soil salinity	❍	■	❍	❍	■	❍	■
Decreased peak flood elevation	■	■	■	■	■	■	■
Decreased flood energy	■	■	■	■	■	■	■
Increased infiltration of surface runoff	■	■	■	■	■	■	■
Increased interflow and subsurface flow to and within stream corridor	■	■	❍	❍	■	■	■
Increased ground water recharge and aquifer volumes	■	■	■	■	■	■	■
Decreased depth to ground water	■	■	■	■	■	■	■
Increased ground water inflow to stream	■	■	■	❍	■	■	■
Decreased flow velocities	■	■	■	■	■	■	■
Increased stream meander	❍	❍	❍	❍	❍	■	❍
Increased stream stability	■	■	■	❍	■	■	■
Decreased stream migration	■	■	■	❍	■	■	■
Reduced channel widening and downcutting	■	■	■	❍	■	■	■
Decreased stream gradient and increased energy dissipation	■	■	❍	❍	❍	■	■
Decreased flow frequency	■	■	■	❍	■	❍	■
Increased flow duration	■	■	■	❍	■	■	■
Increased capacity of floodplain and upland	■	■	■	■	■	❍	■
Decreased sediment and contaminants	■	■	■	■	■	❍	■
Increased capacity of stream	■	■	❍	❍	❍	■	❍
Increased stream capacity to assimilate nutrients/pesticides	■	■	❍	❍	❍	■	❍
Enhanced stream channel with more opportunity for habitat development	■	■	❍	❍	❍	■	❍
Decreased streambank erosion and channel scour	■	■	❍	❍	❍	■	■
Decreased bank failure	■	■	❍	❍	❍	■	❍
Gain of instream organic matter and related decomposition	■	■	❍	❍	❍	■	❍
Decreased instream sediment, salinity, or turbidity	■	■	■	■	■	■	■
Decreased instream nutrient enrichment, siltation, and contaminants leading to eutrophication	■	■	■	■	■	■	■
Connected stream corridor with increased linear distribution of habitat and edge effect	■	■	❍	❍	■	■	■
Gain of edge and interior habitat	■	■	■	■	■	■	■
Increased connectivity and dimension (width) within corridor and to associated ecosystems	■	■	■	■	■	■	■
Increased movement of flora and fauna species for seasonal migration, dispersal repopulation	■	■	■	■	■	■	■
Decrease of opportunistic species, predators	■	■	❍	❍	■	■	■
Decreased exposure to solar radiation, weather, and temperature	■	■	■	■	■	■	■
Decreased temperature and moisture extremes in corridor	■	■	■	■	■	■	■
Increased riparian vegetation	■	■	❍	❍	■	■	■
Increased source of in stream shade, detritus, food, and cover	■	■	❍	❍	■	■	■
Increase of edge diversity	■	■	■	■	■	■	■
Decreased water temperature	■	■	■	■	■	■	■
Enhanced aquatic habitat	■	■	❍	❍	❍	■	❍
Increased invertebrate population	■	■	❍	❍	❍	■	❍
Increased wetland function	■	■	❍	❍	❍	■	■
Increased instream oxygen	■	■	■	❍	❍	■	■
Decrease of exotic species	■	■	❍	❍	■	❍	■
Increased gene pool	■	■	■	■	■	■	■
Increased species diversity	■	■	■	■	■	■	■

■ Measure contribute directly to resulting effect

❍ Measure contribute little to resulting effect

Forest Roads

The vast majority of the restoration design necessary following timber harvest is usually devoted to the road system, where the greatest alteration of soil conditions has taken place. Inadequate drainage, poor location, improperly sized and maintained culverts, and lack of erosion control measures on road prisms, cut-and-fill slopes, and ditches are problems common to a poor road design (Stoner and McFall 1991). The most extreme road system rehabilitation requires full road closure. Full road closure involves removal of culverts and restoration of the streams that were crossed. It can also involve the ripping or tilling of road surfaces to allow plant establishment. If natural vegetation has not already invaded areas of exposed soils, planting and seeding might be necessary.

Full closure might not be a viable alternative if roads are needed to provide access for other uses. In these circumstances a design to restrict traffic might be appropriate. Voluntary traffic control usually cannot be relied on, so traffic barriers like gates, fences, or earth berms could be necessary. Even with traffic restriction, roads require regular inspection for existing or potential maintenance needs. The best time for inspection is during or immediately after large storms or snowmelt episodes so the effectiveness of the culverts and road drainage features can be witnessed first-hand. Design should address regular maintenance activities including road grading, ditch cleaning, culvert cleaning, erosion control vegetation establishment, and vegetation management.

Buffer Strips in Forestry

Forested buffer strips are generally more effective in reducing sediment and chemical loadings in the stream corridor than vegetated filter strips (VFS). However, they are susceptible to similar problems with concentrated flows. Buffers constructed as part of a conservation system increase effectiveness. A stiff-stemmed grass hedge could be planted upslope of either a VFS or a woody riparian forest buffer. The stiff-stemmed grass hedge keeps sediment out of the buffer and increases shallow sheet flow through the buffer.

Most state BMPs also have special sections devoted to limitations for forest management activities in riparian "buffer strips" (also referred to as Streamside Management Zones or Streamside Protection Zones).

Budd et al. (1987) developed a procedure for determining buffer widths for streams within a single watershed in the Pacific Northwest. They focused their attention primarily on maintenance of fish and wildlife habitat quality (stream temperature, food supply, stream structure, sediment control) and found that effective buffer widths varied with the slope of adjacent uplands, the distribution of wetlands, soil and vegetation characteristics, and land use. They concluded that practical determinations of stream buffer width can be made using such analyses, but it is clear that a generic buffer width which would provide habitat maintenance while satisfying human demands does not exist. The determination of buffer widths involves a broad perspective that integrates ecological functions and land use. The section on design approaches to common effects at the beginning of this chapter also includes some discussion on stream buffer width.

Stream corridors have varied dimensions, but stream buffer strips have legal dimensions that vary by state (**Table 8.10**). The buffer may be only part of the corridor or it may be all of it. Unlike designing stream corridors for recreation features or grazing use, designing for timber harvest and related forest management activities is quite regimented by law and regulation. Specific requirements vary from state to state; the state Forester's office or local Extension Service can provide guidance on regulatory issues. USDA Natural Resource Conservation Service offices and Soil and Water Conservation District offices also are sources of information. Refer to Belt et al. (1992) and Welsch (1991) for guidance on riparian buffer strip design, function, and management. Salo and Cundy (1987) provide information on forestry effects on fisheries.

Grazing

The closer an ecosystem is managed to allow for natural ecological processes to function, the more successful a restoration strategy will be. In stream corridors that have been severely degraded by grazing, rehabilitation should begin with grazing management to allow for vegetative recovery.

Vegetative recovery is often more effective than installing a structure. The vegetation maintains itself in perpetuity, allows streams to function in ways that artificial structures cannot replicate, and provides resiliency that allows riparian systems to withstand a variety of environmental conditions (Elmore and Beschta 1987)

Designs that promote vegetative recovery after grazing are beneficial in a number of ways. Woody species can provide resistance to channel erosion and improve channel stability so that other species can become established. As vegetation becomes established, channel elevation will increase as sediment is deposited within and along the banks of the channel (aggradation), and water tables will rise and may reach the root zone of plants on former terraces or floodplains. This aggradation of the channel and the rising wa-

BMP Implementation and Section 9 of the Clean Water Act

Section 319 of the Clean Water Act of 1987 required the states to identify and submit BMPs for USEPA approval to help control nonpoint sources of pollution. As of 1993, 41 of 50 states had EPA-approved voluntary or regulatory BMP programs dealing with silvicultural (forest management) activities. The state BMPs are all similar; the majority deal with roads. Montana, for example, has a total of 55 specifically addressed forest practices. Of those 55 practices, 35 deal with road planning and location, road design, road maintenance, road drainage, road construction, and stream crossings.

Table 8.10: Buffer strip requirements by state.

State	**Stream Class**	**Buffer Strip Requirements**		
		Width	**Shade or Canopy**	**Leave Trees**
Idaho	**Class I***	Fixed minimum (75 feet)	75% current shade[a]	Yes, number per 1000 feet, dependent on stream width[b]
	Class II**	Fixed minimum (5 feet)	None	None
Washington	**Type 1, 2, and 3***	Variable by stream width (5 to 100 feet)	50%, 75% if temperature > 60ºF	Yes, number per 1000 feet, dependent on stream width and bed material
	Type 4**	None	None	25 per 1000 feet, 6 inches diameter
California	**Class I and Class II***	Variable by slope and stream class (50 to 200 feet)	50% overstory and/or understory; dependent on slope and stream class	Yes; number to be determined by canopy density
	Class III**	None[b]	50% understory[e]	None[e]
Oregon	**Class I****	Variable, 3 times stream width (25 to 100 feet)	50% existing canopy, 75% existing shade	Yes; number per 1000 feet and basal area per 1000 feet by stream width
	Class II special protection**	None[f]	75% existing shade	None

* Human water supply or fisheries use.
** Streams capable of sediment transport (CA) or other influences (ID and WA) or significant impact (OR) on downstream waters.
[a] In ID, the shade requirement is designed to maintain stream temperatures.
[b] In ID, the leave tree requirement is designed to provide for recruitment of large woody debris.
[c] May range as high as 300 feet for some types of timber harvest.
[d] To be determined by field inspection.
[e] Residual vegetation must be sufficient to prevent degradation of downstream beneficial uses.
[f] In eastern OR, operators are required to "leave stabilization strips of undergrowth... sufficient to prevent washing of sediment into Class I streams below."

CASE STUDY

Pacific Northwest Floods of 1996

Floods, Landslides, and Forest Management— 'The Rest of The Story'

*Warm winds, intense rainfall, and rapid snowmelt during the winter of 1995-96 and again in the winter of 1996-97 caused major flooding, landslides, and related damage throughout the Pacific Northwest **(Figure 8.54)**. Such flooding had not been seen for more than 30 years in hard-hit areas. Damage to roads, campgrounds, trails, watersheds, and aquatic resources was widespread on National Forest Service lands. These events offered a unique opportunity to investigate the effects of severe weather, examine the influence and effectiveness of various forest management techniques, and implement a repair strategy consistent with ecosystem management principles.*

The road network in the National Forests was heavily damaged during the floods. Decisions about the need to replace roads are based on long-term access and travel requirements. Relocation of roads to areas outside floodplains is a measure being taken. Examination of road crossings at streams concluded with design recommendations to keep the water moving, align culverts horizontally and longitudinally with the stream channel, and minimize changes in stream channel cross section at inlet basins to prevent debris plugs.

Many river systems were also damaged. In some systems, however, stable, well-vegetated slopes and streambanks combined with fully functioning floodplains buffered the effects of the floods. Restoration efforts will focus on aiding natural processes in these systems.

Figure 8.54: 1996 Landslides.
(a) April landslide: debris took out the track into the Greenwater River and (b) July landslide: debris took out the road and deposited debris into the river.

Streambank stabilization and riparian plantings will be commonly used. Examination of instream structure durability concluded that structures are more likely to remain in place if they are in fourth-order or smaller streams and are situated in a manner that maintains a connection between the structure and the streambank. They will be most durable in watersheds with low landslide/debris torrent frequency.

ter table allow more water to be stored during wet seasons, thereby prolonging flow even during periods of drought (Elmore and Beschta 1987).

Kauffman et al. (1993) observed that fencing livestock out of the riparian zone is the only grazing strategy that consistently results in the greatest rate of vegetative recovery and the greatest improvement in riparian function. However, fencing is very expensive, requires considerable maintenance, and can limit wildlife access—a negative impact on habitat or conduit functions.

Some specialized grazing strategies hold promise for rehabilitating less severely impacted riparian and wetland areas without excluding livestock for long periods of time. The efficiency of a number of grazing strategies with respect to fishery needs are summarized in **Tables 8.11 and 8.12** (from Platts 1989). They summarize the influence of grazing systems and stream system characteristics on vegetation response, primarily from a western semiarid perspective. Some general design recommendations for selecting a strategy include the following (Elmore and Kauffmann 1994):

- Each strategy must be tailored to a particular stream or stream reach. Management objectives and components of the ecosystem that are of critical value must be identified (i.e., woody species recovery, streambank restoration, increased habitat diversity, etc.). Other information that should be identified includes present vegetation, potential of the site for recovery, the desired future condition, and the current factors causing habitat degradation or limiting its recovery.
- The relationships between ecological processes that must function for riparian recovery should be described. Factors affecting present condition (i.e., management stress vs. natural stress) and conditions required for the stream to resume natural functions need to be assessed. Anthropogenic factors caus-

Table 8.11: Evaluation and rating of grazing strategies.

Strategy[a]	Level to Which Riparian Vegetation is Commonly Used	Control of Animal Distribution (Allotment)	Streambank Stability	Brushy Species Condition	Seasonal Plant Regrowth	Stream Riparian Rehabilitation Potential	Fishery Needs Rating[b]
Continuous season-long (cattle)	Heavy	Poor	Poor	Poor	Poor	Poor	1
Holding (sheep or cattle)	Heavy	Excellent	Poor	Poor	Fair	Poor	1
Short duration-high intensity (cattle)	Heavy	Excellent	Poor	Poor	Poor	Poor	1
Three herd-four pasture (cattle)	Heavy to moderate	Good	Poor	Poor	Poor	Poor	2
Holistic (cattle or sheep)	Heavy to light	Good	Poor to good	Poor	Good	Poor to excellent	2-9
Deferred (cattle)	Moderate to heavy	Fair	Poor	Poor	Fair	Fair	3
Seasonal suitability (cattle)	Heavy	Good	Poor	Poor	Fair	Fair	3
Deferred-rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Stuttered deferred-rotation (cattle)	Heavy to moderate	Good	Fair	Fair	Fair	Fair	4
Winter (sheep or cattle)	Moderate to heavy	Fair	Good	Fair	Fair to good	Good	5
Rest-rotation (cattle)	Heavy to moderate	Good	Fair to good	Fair	Fair to good	Fair	5
Double rest-rotation (cattle)	Moderate	Good	Good	Fair	good	Good	6
Seasonal riparian preference (cattle or sheep)	Moderate to light	Good	Good	Good	Fair	Fair	6
Riparian pasture (cattle or sheep)	As prescribed	Good	Good	Good	Good	Good	8
Corridor fencing (cattle or sheep)	None	Excellent	Good to excellent	Good to excellent	Good	Excellent	9
Rest-rotation with seasonal preference (sheep)	Light	Good	Good to excellent	Good to excellent	Good	Excellent	9
Rest or closure (cattle or sheep)	None	Excellent	Excellent	Excellent	Excellent	Excellent	10

[a] Jacoby (1989) and Platts (1989) define these management strategies

[b] Rating scale based on 1 (poorly compatible) to 10 (highly compatible with fishery needs)

Table 8.12: Generalized relationships between grazing systems, stream system characteristics, and riparian vegetation response.

Grazing System	Steep Low Sediment Load	Steep High Sediment Load	Moderate Low Sediment Load	Moderate High Sediment Load	Flat Low Sediment Load	Flat High Sediment Load
No grazing	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Winter or dormant season	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Early growing season	Shrubs + Herbs + Banks 0	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Deferred or late season	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Three-pasture rest rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Deferred rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks + to 0	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs + Herbs + Banks +
Early rotation	Shrubs + Herbs + Banks 0 to –	Shrubs + Herbs + Banks 0 to +	Shrubs + Herbs + Banks + to 0	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +	Shrubs + Herbs + Banks +
Rotation	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to –	Shrubs – Herbs + Banks 0 to +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +	Shrubs – Herbs + Banks +
Season-long	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –
Spring and fall	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks 0 to +
Spring and summer	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks 0 to –	Shrubs – Herbs – Banks –	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks – to 0	Shrubs – Herbs – Banks 0 to +

Note: – = decrease; + = increase; 0 = no change. Stream gradient: 0 to 2% = flat; 2 to 4% = moderate; > 4% = steep. Banks refers to bank stability.

ing stream degradation must be identified and changed.

- Design and implementation should be driven by attainable goals, objectives, and management activities that will achieve the desired structure and functions.
- Implementation should include a monitoring plan that will evaluate management, allowing for corrections or modifications as necessary, and a strong compliance and use supervision program.

The main consideration for selecting a grazing system is to have an adequate vegetative growing season between the period of grazing and timing of high-energy runoff. It is impossible to provide a cookie-cutter grazing strategy for every stream corridor; designs have to be determined on the ground, stream by stream, manager by manager. Simply decreasing the number of livestock is not a solution to degraded riparian conditions; rather, restoring these degraded areas requires fundamental changes in the ways that livestock are grazed (Chaney et al. 1990).

Clearly, the continued use of grazing systems that do not include the functional requirements of riparian vegetation communities will only perpetuate riparian problems (Elmore and Beschta 1987). Kinch (1989) and Clary and Webster (1989) provide greater detail on riparian grazing management and designing alternative grazing strategies. Chaney et al. (1990) present photo histories of a number of interesting grazing restoration case studies, and of the short-term results of some of the available grazing strategies.

Mining

Post-mining reclamation of stream corridors must begin with restoration of a properly functioning channel. Because many of the geologic and geomorphic controls associated with the pre-disturbance channel may have been obliterated by mining operations, design of the post-mining channel often requires approaches other than mimicking the pre-disturbance condition. Channel alignment, slope, and size may be determined on the basis of empirical relations developed from other streams in the same hydrologic and physiographic settings (e.g., Rechard and Schaefer 1984, Rosgen 1996). Others (e.g., Has-further 1985) have used a combination of empirical and theoretical approaches for design of reclaimed channels. Total reconstruction of stream channels is treated at length in Section 8.E. Other sections of the chapter address stabilization of streambanks, revegetation of floodplains and terraces, and restoration of aquatic and terrestrial habitats. Additional guidance is available in Interfluve, Inc. (1991).

Surface mining is usually associated with large-scale disturbances in the contributing watershed, therefore, a rigorous hydrological analysis of pre- and post-mining conditions is critical for stream corridor restoration of disturbed systems. The hydrologic analysis should include a frequency analysis of extreme high- and low-flow events to assess channel performance in the post-mining landscape.

Hydrologic modeling may be required to generate runoff hydrographs for the post-mining channel because watershed geology, soils, vegetation, and topography may be completely altered by mining operations. Thus, channel design and stability assessments will be based on modeled runoff rates reflecting expected watershed conditions. The hydrologic analysis for post-mining restoration should also address sediment production from the reclaimed landscape. Sediment budgets (see Chapter 7) will be needed for both the period of vegetation establishment and the final revegetated condition.

The hydrologic analyses will provide restoration practitioners with the flow and sediment characteristics needed for restoration design. The analyses may also indicate a need for at least temporary runoff detention and sediment retention during the period of vegetation establishment. However, the post-mining channel should be designed for long-term equilibrium with the fully reclaimed landscape. Water quality issues (e.g., acid mine drainage) often control the feasibility of stream restoration in mined areas and should be considered in design.

CASE STUDY

Oven Run, Pennsylvania

The effects of abandoned mines draining into the surrounding lands cause dramatic changes in the area ***(Figure 8.55(a))****. Runoff with high levels of minerals and acidity can denude the ground of vegetation, expose the soil, and allow erosion with the sediment further stressing streams and wetland. Any efforts to restore streams in this environment must deal with the problem if any success is to be likely.*

The Natural Resources Conservation Service, formerly known as the Soil Conservation Service, has been working on the Oven Run project along with the Stonycreek Conemaugh River Improvement (SCRIP) to improve water quality in a 4-mile reach above the Borough of Hooversville. SCRIP is a group of local and state government as well as hundreds of individuals interested in improving the water quality in an area on Pennsylvania's Degraded Watersheds list.

The initial goal of improving water quality resulted in improving habitat and aesthetic qualities. The water coming into Hooversville had higher-than-desired levels of iron, manganese, aluminum, sulfate, and acidity. Six former strip mines, which had a range of problems, were identified. They included deep mine openings that have large flows of acid mine drainage, acid mine seepage into streams, eroding spoil areas, areas of ponded water that infiltrate into ground water (adding to the acid mine drainage), and areas downhill of seepage and deep mine drainage that are denuded and eroding.

Control efforts included grading and vegetating the abandoned mine to reduce infiltration through acid-bearing layers and reduce erosion and sedimentation, surface water controls to carry water around the sites to safer outlets, and treating discharge flow with anoxic limestone drains and chambered passive wetland treatments (Figure 8.55(b)). Additionally, 1,000 feet of trees were planted along one of the site streams to shade the Stoneycreek River. Average annual costs for the six sites were estimated to be $503,000 compared to average annual benefits of $513,000.

The sites are being monitored on a monthly basis, and 4 years after work was begun the treatments have had a measurable success. The acid influent has been neutralized, and the effluent is now a net alkaline. Iron, aluminum, and manganese levels have been reduced, with iron now at average levels of 0.5 mg/L from average levels of 35 mg/L.

(a)

Figure 8.55: Stream corridor (a) before and (b) after restoration.

(b)

Recreation

Both concentrated and dispersed recreational use of stream corridors can cause damage and ecological change. Ecological damage primarily results from the need for access for the recreational user. A trail often will develop along the shortest or easiest route to the point of access on the stream.

Additional resource damage may be a function of the mode of access to the stream: motorcycles and horses cause far more damage to vegetation and trails than do pedestrians. Control of streambank access in developed recreation sites must be part of a restoration design. On undeveloped or unmanaged sites, such control is more difficult but still very necessary (**Figure 8.56**).

Rehabilitation of severely degraded recreation areas may require at least temporary use restrictions. Even actively eroding trails, camp and picnic sites, and stream access points can be stabilized through temporary site closure and combinations of soil and vegetation restoration (Wenger 1984, Marion and Merriam 1985, Hammitt and Cole 1987). Closure will not provide a long-term solution if access is restored without addressing the cause of the original problem. Rather, new trails and recreation sites should be located and constructed based on an understanding of vegetation capabilities, soil limitations, and other physical site characteristics.

Basically, the keys to a successful design are:

- Initially locating or moving use to the most damage-resistant sites.
- Influencing visitor use.
- Hardening use areas to make them more resistant.
- Rehabilitating closed sites.

Urbanization

Few land uses have the capacity to alter water and sediment yield from a drainage as much as the conversion of a watershed from rural to urban conditions; thus, few land uses have greater potential to affect the natural environment of a stream corridor.

As a first step in hydrologic analyses, designers should characterize the nature of existing hydrologic response and the likelihood for future shifts in water and sediment yield. Initially, construction activities create excess sediment that can be deposited in downstream channels and floodplains. As impervious cover increases, peak flows increase. Water becomes cleaner as more area is covered with landscaping or impervious material. The increased flows and cleaner water enlarge channels, which increases sediment loads downstream.

Determine if the watershed is (a) fully urbanized, (b) undergoing a new phase of urbanization, or (c) is in the beginning stages of urbanization (Riley, 1998).

An increase in the amount of impervious cover in a watershed leads to increased peak flows and resulting channel enlargement (**Figure 8.57**). Research has shown that impervious cover of as little as 10 to 15 percent of a watershed can have significant adverse effects on channel conditions (Schueler 1996). Magnitudes of channel-forming or bankfull flood events (typically 1- to 3-year recurrence intervals) are increased significantly, and flood events that previously occurred once every year or two may occur as often as one or two times a month.

Enlargement of streams with subsequent increases in downstream sediment loads in urbanized watersheds should be expected and accommodated in the design of restoration treatments.

Procedures for estimating peak discharges are described in Chapter 7, and effects of urbanization on magnitude of peak flows must be incorporated into the analysis. Sauer et al. (1983) investigated the effect of urbanization on peak flows by analyzing 199 urban watersheds in 56 cities and 31 states. The objective of the analysis was to determine the increase in peak discharges due to urbanization and to develop regression equations for estimating design floods, such as the 100-year or 1 percent chance annual flood, for ungauged urban watersheds. Sauer et al. (1983) developed regression equations based on watershed, climatic, and urban characteristics that can be used to estimate the 2, 5, 10, 25, 50, 100, and 500-year urban annual peak discharges for ungauged urban watersheds. The equation for the 100-year flood in cubic feet per second (UQ100) is provided as an example:

$$UQ100 = 2.50\ A^{.29}\ SL^{.15}\ (RI2+3)^{1.26}\ (ST+8)^{-.52}\ (13\text{–}BDF)^{-.28}\ IA^{.06}\ RQ100^{.63}$$

where the explanatory variables are drainage area in square miles (A), channel slope in feet per mile (SL), the 2-year, 2-hour rainfall in inches (RI2), basin storage in percent (ST), basin development factor (BDF), which is a measure of the extent of development of the drainage system (dimensionless, ranging from 0 to 12), percent impervious area (IA), and the equivalent rural peak discharge in cubic feet per

Figure 8.56: Controlled access. *Control of streambank access is an important part of the restoration design.*
Source: J. McShane.

Figure 8.57: Storm water flow on a paved surface. *Impervious surfaces increase peak flows and can result in channel enlargement.*
Source: M. Corrigan.

second (RQ100) in the example equation above.

Sauer et al. (1983) provide the allowable range for each variable. The two indices of urbanization in the equation are BDF and IA. They can be used to adjust the rural peak discharge RQ100 (either estimated or observed) to urban conditions.

Sauer et al. (1983) provide equations like the one above and graphs that relate the ratio of the urban to rural peak discharge (UQx/RQx) for recurrence intervals x = 2, 10, and 100 years. The 2- year peak ratio varies from 1.3 to 4.3, depending on the values of BDF and IA; the 10-year ratio varies from 1.2 to 3.1; and the 100-year ratio varies from 1.1 to 2.6. These ratios indicate that urbanization generally has a lesser effect on higher-recurrence-interval floods because watershed soils are more saturated and floodplain storage more fully depleted in large floods, even in the rural condition.

More sophisticated hydrologic analyses than the above are often used, including use of computer models, regional regression equations, and statistical analyses of gauge data. Hydrologic models, such as HEC-1 or TR-20, are often already developed for some urban watersheds.

Once the flood characteristics of the stream are adjusted for urbanization, new equilibrium channel dimensions can be estimated from hydraulic geometry relationships developed using data from stable, alluvial channels in similar (soils, slope, degree of urbanization) watersheds, or other analytical approaches. Additional guidance for design of restored channels is provided earlier in this chapter in the section on channel reconstruction.

Changes in flooding caused by urbanization of a watershed can be mitigated during urban planning through practices designed to control storm runoff. These practices emphasize the use of vegetation and biotechnical methods, as well as structural methods, to maintain or restore water quality and dampen peak runoff rates. Strategies for controlling runoff include the following:

- Increasing infiltration of rainfall and streamflow to reduce runoff and to remove pollutants.
- Increasing surface and subsurface storage to reduce peak flows and induce sediment deposition.
- Filtration and biological treatment of suspended and soluble pollutants (i.e., constructed wetlands).
- Establishment and/or enhancement of forested riparian buffers.
- Management of drainage from the transportation network.
- Introduction of trees, shrubs, etc., for various restoration purposes.

In addition to changes in water yield, urbanization of a watershed frequently generates changes in its sediment yield. In humid climates, vegetative cover prior to urbanization often is adequate to protect soil resources and minimize natural erosion, and the combination of impervious area and vegetation of a fully urban watershed might be adequate to minimize sediment yield. During the period of urbanization, however, sediment yields increase significantly as vegetation is cleared and bare soil is exposed during the construction process. In more arid climates, sediment yield from an urban watershed may actually be lower than the yield from a rural watershed due to the increased impervious area and vegetation associated with landscaping, but the period of urbanization (i.e., construction) is still the time of greatest sediment production.

The effect of urbanization on sediment discharge is illustrated in **Figure 8.58**, which contains data from nine sub-basins in a 32-square-mile area in the Rock Creek and Anacostia River Basins north of Washington, DC (Yorke and Herb 1978). During the period of data collection (1963-74), three subbasins remained virtually rural while the others underwent urban development. In 1974, urban land represented from 0 to 60 percent of land use in the nine subbasins. These data were used to develop a relation between suspended sediment yield and the percentage of land under construction. This relation indicated that suspended sediment yield increased about 3.5 times for watersheds with 10 percent of the land area under construction. However, suspended-sediment yields for watersheds where sediment controls (primarily sediment basins) were employed for 50 percent of the construction area were only about one-third of these for areas without controls. The effect of controls is seen in the figure. The three curves present growing season data for three periods of increasing sediment control: 1963-

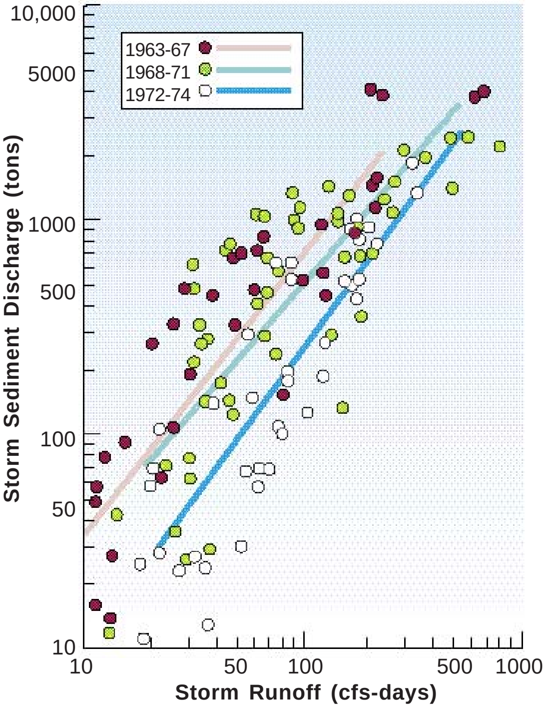


Figure 8.58: Sediment-transport curves for growing season storms. *The effect of urbanization on sediment discharge is illustrated from data collected in a 32-square-mile area.*

67, when no controls were used on construction sites; 1968-71, when controls were mandatory; and 1972-74, when controls were mandatory and subject to inspection by county officials. It further illustrates that storm runoff is not the only factor affecting storm sediment discharge as evidenced by the significant scatter about each relation.

In addition to sediment basins, management practices for erosion and sediment control focus on the following objectives:

- Stabilizing critical areas along and on highways, roads, and streets.
- Siting and placement of sediment migration barriers.
- Design and location of measures to divert or exclude flow from sensitive areas.
- Protection of waterways and outlets.
- Stream and corridor protection and enhancement.

All of these objectives emphasize the use of vegetation for sediment control. Additional information on BMPs for controlling runoff and sediment in urban watersheds can be found in the *Techniques Appendix.*

In theory, a local watershed management plan might be the best tool to protect a stream corridor from the cumulative impact of urban development; however, in practice, few such plans have realized this goal (Schueler 1996). To succeed, such plans must address the amount of bare ground exposed during construction and the amount of impervious area that will exist during and after development of the watershed. More importantly, success will depend on using the watershed plan to guide development decisions, and not merely archiving it as a one-time study whose recommendations were read once but never implemented (Schueler 1996).

Key Tools of Urban Stream Restoration Design

Restoration design for streams degraded by prior urbanization must consider pre-existing controls and their effects on restoration objectives. Seven restoration tools can be applied to help restore urban streams. (Schereler,1996) These tools are intended to compensate for stream functions and processes that have been diminished or degraded by prior watershed urbanization. The best results are usually obtained when the following tools are applied together.

Tool 1. Partially restore the predevelopment hydrological regime. The primary objective is to reduce the frequency of bankfull flows in the contributing watershed. This is often done by constructing upstream storm water retrofit ponds that capture and detain increased storm water runoff for up to 24 hours before release (i.e., extended detention). A common design storm for extended detention is the one-year, 24 hour storm event. Storm water retrofit ponds are often critical in the restoration of small and midsized streams, but may be impractical in larger streams and rivers.

Tool 2. Reduce urban pollutant pulses. A second need in urban stream restoration is to reduce concentrations of nutrients, bacteria and toxics in the stream, as well as trapping excess sediment loads. Generally, three tools can be applied to reduce pollutant inputs to an urban stream: storm water retrofit ponds or wetlands, watershed pollution prevention programs, and the elimination of illicit or illegal sanitary connections to the storm sewer network

Tool 3. Stabilize channel morphology. Over time, urban stream channels enlarge their dimensions, and are subject to severe bank and bed erosion. Therefore, it is important to stabilize the channel, and if possible, restore equilibrium channel geometry. In addition, it is also useful to provide undercuts or overhead cover to improve fish habitat. Depending on the stream order, watershed impervious cover and the height and angle of eroded banks, a series of different tools can be applied to stabilize the channel, and prevent further erosion. Bank stabilization measures include imbricated rip-rap, brush bundles, soil bioengineering methods such as willow stakes and biologs, lunker structures and rootwads. Grade stabilization measures are discussed earlier in this chapter and in Appendix A.

Tool 4. Restore Instream habitat structure. Most urban streams have poor instream habitat structure, often typified by indistinct and shallow low flow channels within a much larger and unstable storm channel. The goal is to restore instream habitat structure that has been blown out by erosive floods. Key restoration elements include the creation of pools and riffles, confinement and deepening of the low flow channels, and the provision of greater structural complexity across the streambed. Typical tools include the installation of log checkdams, stone wing deflectors and boulder clusters along the stream channel.

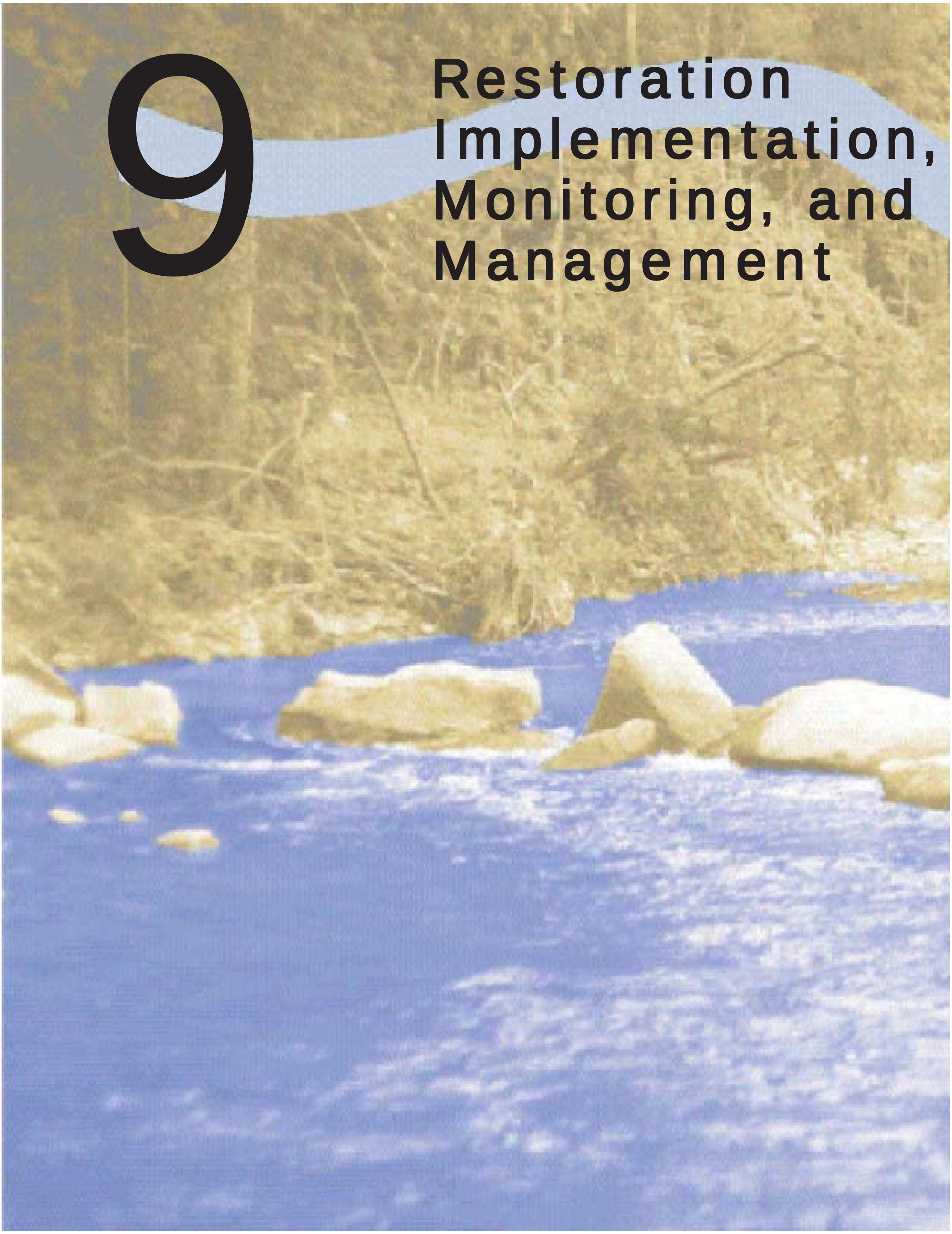
Tool 5. Reestablish Riparian Cover. Riparian cover is an essential component of the urban stream ecosystem. Riparian cover stabilizes banks, provides large woody debris and detritus, and shades the stream. Therefore, the fifth tool involves reestablishing the riparian cover plant community along the stream network. This can entail active reforestation of native species, removal of exotic species, or changes in mowing operations to allow gradual succession. It is often essential that the riparian corridor be protected by a wide urban stream buffer.

Tool 6. Protect critical stream substrates. A stable, well sorted streambed is often a critical requirement for fish spawning and secondary production by aquatic insects. The bed of urban streams, however, is often highly unstable and clogged by fine sediment deposits. It is often necessary to apply tools to restore the quality of stream substrates at points along the stream channel. Often, the energy of urban storm water can be used to create cleaner substrates— through the use of tools such as double wing deflectors and flow concentrators. If thick deposits of sediment have accumulated on the bed, mechanical sediment removal may be needed.

Tool 7. Allow for recolonization of the stream community. It may be difficult to reestablish the fish community in an urban stream if downstream fish barriers prevent natural recolonization. Thus, the last urban stream restoration tool involves the judgment of a fishery biologist to determine if downstream fish barriers exist, whether they can be removed, or whether selective stocking of native fish are needed to recolonize the stream reach.

9

Restoration Implementation, Monitoring, and Management



9.A Restoration Implementation

- What are passive forms of restoration and how are they “implemented”?
- What happens after the decision is made to proceed with an active rather than a passive restoration approach?
- What type of activities are involved when installing restoration measures?
- How can impact on the stream channel and corridor be minimized when installing restoration measures (e.g, water quality, air quality, cultural resources, noise)?
- What types of equipment are needed for installing restoration measures?
- What are some important considerations regarding construction activities in the stream corridor?
- How do you inspect and evaluate the quality and impact of construction activities in the stream corridor?
- What types of maintenance measures are necessary to ensure the ongoing success of a restoration?

9.B Monitoring Techniques Appropriate for Evaluating Restoration

- What methods are available for monitoring biological attributes of streams?
- What can assessment of biological attributes tell you about the status of the stream restoration?
- What physical parameters should be included in a monitoring management plan?
- How are the physical aspects of the stream corridor evaluated?
- How is a restoration monitoring plan developed, and what issues should be addressed in the plan?
- What are the sampling plan design issues that must be addressed to adequately detect trends in stream corridor conditions?
- How do you ensure that the monitoring information is properly collected, analyzed, and assessed (i.e., quality assurance plans)?

9.C Restoration Management

- What are important management priorities with ongoing activities and resource uses within the stream corridor?
- What are some management decisions that can be made to support stream restoration?
- What are some example impacts and management options with various types of resource use within the stream corridor (e.g., forest management, grazing, mining, fish and wildlife, urbanization)?
- When is restoration complete?

9

Restoration Implementation, Monitoring, and Management

9A Restoration Implementation
9B Monitoring Techniques Appropriate for Evaluating Restoration
9.C Restoration Management

Figure 9.1: A restored stream. *Stream corridor restoration measures must be properly installed, monitored, and managed to be successful.*

Completion of the restoration design marks the beginning of several important tasks for the stream restoration practitioner. Emphasis must now be placed on prescribing or implementing restoration measures, monitoring and assessing the effectiveness of the restoration, and managing the design to achieve the desired stream corridor conditions (**Figure 9.1**).

Implementation, management, and monitoring/ evaluation may proceed as part of a larger setting, or they may be considered components of a corridor-specific restoration effort. In either case, they require full planning and commitment before the restoration plan is implemented. The technical complexity of a project must be determined by the restoration practitioner based on available resources, technology, and what is necessary to achieve restoration goals. There must be reasonable assurance that there will be continuing access for ongoing inspection, maintenance, emergency repairs, management, and monitoring activities as well. All cooperators should be aware that implementation, monitoring, and management might require unanticipated work, and that plans and objectives might change over time as knowledge improves or as changes occur.

This chapter builds on the discussion of restoration implementation, monitoring, evaluation, and adaptive management presented in Chapter 6. Specifically, it moves beyond the planning components associated with these key restoration activities and discusses some of the technical issues and elements that restoration practitioners must consider when installing, monitoring, and managing stream corridor restoration measures. The discussion that follows is divided into three major sections.

Section 9.A:
Restoration Implementation

This first section describes the implementation of restoration measures beyond just removing disturbance factors and taking other passive approaches that allow the stream corridor to restore itself over time. Technical considerations relating to site preparation, site clearing, construction, inspection, and maintenance are discussed in this section.

Section 9.B:
Monitoring Techniques Appropriate for Evaluating Restoration

The purpose of restoration monitoring is to gather data that will help to determine the success of the restoration effort. This section presents some of the monitoring techniques appropriate for evaluating restoration.

Section 9.C:
Restoration Management

Management of the restoration begins with the implementation of the plan. The "adaptive management" approach was presented in Chapter 6 as an important part of the planning process. It provides the flexibility to detect when changes are needed to achieve success and to be able to make the necessary midcourse, short-term corrections.

Ideally, the long-term management of a successful restoration will involve only periodic monitoring to check that the system is sustaining itself through natural processes.However, this is rarely the case for stream corridors in human-inhabited landscapes.

New crops, markets, and government programs can rapidly and significantly alter the physical, chemical, and biological characteristics of stream corridors and their watersheds, destroying restoration efforts. Conversion of rural lands and wildlands to urban uses and exploitation of natural resources can change the landscape and cause natural processes to become unbalanced, leaving the stream corridor with no way to sustain itself.

Additionally, natural imbalances can occur due to local and regional climatic changes, predation, disease, fire, genetic changes, and catastrophes like earthquakes, hurricanes, tornadoes, volcanic eruptions, land-slides, and floods. Long-term management of the restored stream corridor will therefore require vigilance, anticipation, and reaction to future changes.

9.A Restoration Implementation

Implementation of stream corridor restoration must be preceded by careful planning. Such planning should include the following (at a minimum):

- Determining a schedule.
- Obtaining necessary permits.
- Conducting preimplementation meetings.
- Informing and involving property owners.
- Securing site access and easements.
- Locating existing utilities.
- Confirming sources of materials and ensuring standards of materials.

The careful execution of each planning step will help ensure the success of the restoration implementation. Full restoration implementation, however, involves several actions that require careful execution as well as the cooperation of several participants. See Chapters 4 and 5 for specific guidance on planning a stream corridor initiative.

Site Preparation

Site preparation is the first step in the implementation of restoration measures. Preparing the site requires that the following actions be taken.

Delineating Work Zones

The area in which restoration occurs is defined by many disparate factors. This area is determined most fundamentally by the features of the landscape that must be affected to achieve restoration goals. Boundaries of property ownership, restrictions imposed by permit requirements, and natural or cultural features that might have special significance can also determine the *work zone*. A heavy-equipment operator or crew supervisor cannot be expected to be aware of the multiple requirements that govern where work can occur. Thus, delineation of those zones in the field should be the first activity conducted on the site. The zones should be marked by visible stakes and more preferably by temporary fencing (usually a bright-colored sturdy plastic netting). This delineation should conform to any special restrictions noted or temporary stakes placed during the preconstruction meeting between the project manager and field inspector.

Major Elements of Restoration Implementation

- *Review of Plans*
- *Site Preparation*
- *Site Clearing*
- *Installation and Construction*
- *Site Reclamation/Cleanup*
- *Inspection*
- *Maintenance*

Preparing Access and Staging Areas

A site is often accessed from a public road in an upland portion of the site. Ideally, for convenience, a staging area for crew, equipment, and materials can be located near an access road close to the restoration site but out of the stream corridor and away from wetlands or areas with highly erodible soils. The staging area should also be out of view from public thoroughfares, if possible, to increase security.

Although property ownership, topography, and preexisting roads make access to every site unique, several principles should guide design, placement, and construction of site access:

- Avoid any sensitive wildlife habitat or plant areas or threatened and endangered species and their designated critical habitat.
- Avoid crossing the stream if at all possible; where crossing is unavoidable, a bridge is almost mandatory.
- Minimize slope disturbance since effective erosion control is difficult on a sloped roadway that will be heavily used.
- Construct roadways with low gradients; ensure that storm water runoff drains to outlets; install an adequate roadbed; and, if possible, set up a truck-washing station at the entrance of the construction site to reduce off- site transport of mud and sediment by vehicles.
- In the event of damage to any private or public access roads used to transport equipment or heavy materials to and from the site, those responsible should be identified and appropriate repairs should be made.

Taking Precautions to Minimize Disturbance

Every effort should be made to minimize and, where possible, avoid site disturbance. Emphasis should be placed on addressing protection of existing vegetation and sensitive habitat, erosion and sediment control, protecting air and water quality, protecting cultural resources, minimizing noise, and providing for solid waste disposal and worksite sanitation.

Protection of Existing Vegetation and Sensitive Habitat

Fencing can be an effective way to ensure protection of areas within the construction site that are to remain undisturbed (e.g., vegetation designated to be preserved, sensitive terrestrial habitat, or sensitive wetland habitat).

As in delineating work zones, fencing should be placed around all protected areas during initial site preparation, even before the access road is fully constructed, if possible, but certainly before wholesale earthmoving begins. Fencing material should be easy to see, and areas should be labeled as protection areas. Caution should always be exercised when grading is planned adjacent to a protected area.

Erosion

Many well-established principles of effective erosion and sediment control can be readily applied to stream corridor restoration (Goldman et al. 1986). Every effort should be made to prevent erosion because prevention is always more effective than having to trap already- eroded sediment particles in runoff. Erosion and sediment controls should be installed during initial site preparation.

The most basic method of control is physical screening of areas to remain undisturbed. Properly chosen, installed, and maintained sediment control measures can provide a significant degree of filtration for sediment-bearing runoff (**Figure 9.2**).

Where undisturbed areas lie downslope of implementation activities, one method of controlling sediment is the use of a silt fence, which is normally made of filter fabric. Silt fences can provide a significant degree of filtration for sediment-bearing runoff, but only if correctly chosen, installed, and maintained. Design guidelines for silt fences include the following:

- Drainage area of 1 acre or less.
- Maximum contributing slope gradient of 2 horizontal to 1 vertical.
- Maximum upslope distance of 100 ft.
- Maximum flow velocity of 1 ft./sec.

Installation is even more critical

Figure 9.2: Silt fence at a construction site. *Properly chosen and installed silt fences can provide a significant degree of off-site sediment control.*

than material type; most fabric fences fail because either runoff carves a channel beneath them or sediment accumulates against them, causing them to collapse. To help prevent failure, the lower edge of the fabric should be placed in a 4- to 12-inch-deep trench, which is then backfilled with native soil or gravel, and wire fencing should be used to support the fabric.

Figure 9.3 presents example silt fence installation guidelines. Properly installed silt fences commonly fail due to lack of maintenance. One rainfall event can deposit enough sediment that failure will occur during the next rainfall event if the sediment against the fence is not removed.

Straw bales are also common sediment control measures. Bales should be placed in trenches about 4 inches deep, staked into the ground, and placed with their ends (not just corners) abutting each other. **Figure 9.4** presents example straw bale installation guidelines. The limitations on siting are the same as for silt fences, but straw bales are typically less durable and might need to be replaced.

Where the scope of a project is so small that no official erosion control plans have been prepared, control measures should be appropriate to the site, installed promptly, and maintained appropriately.

Proper restoration implementation requires managers to prepare for “unexpected” failure of erosion control measures. By the time moderate to heavy rains can be expected, the following preparations should have been made:

- Additional erosion control materials should be stockpiled on site, including straw bales, filter fabric and wire backing, posts, sand and burlap bags, and channel lining materials (rock, geotextile fabric or grids, jute netting, coconut fabric material, etc.).
- Inspection of the construction site should occur during or immediately after a rain storm or other significant runoff event to determine the effectiveness of sediment control measures.
- A telephone number for the site superintendent or project manager should be made available to neighboring residents if they witness any problems on or coming from the site. Residents should be educated on what to watch for, such as sediment-laden runoff or failed structures.

Erosion and sediment controls should be installed during initial site preparation.

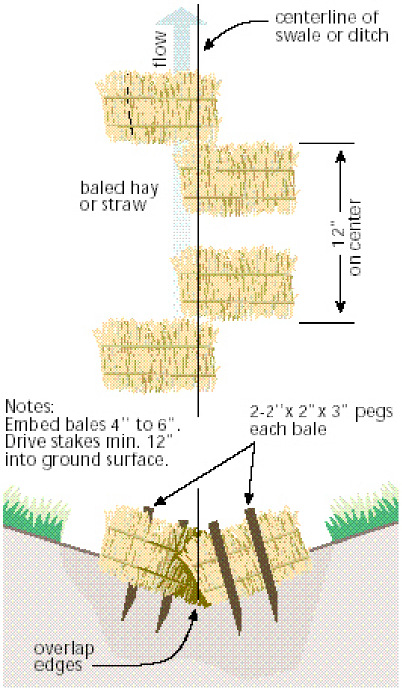


Figure 9.4: Straw bale installation guidelines. *Straw bales are common sediment control measures.*
Source: King County, Washington.

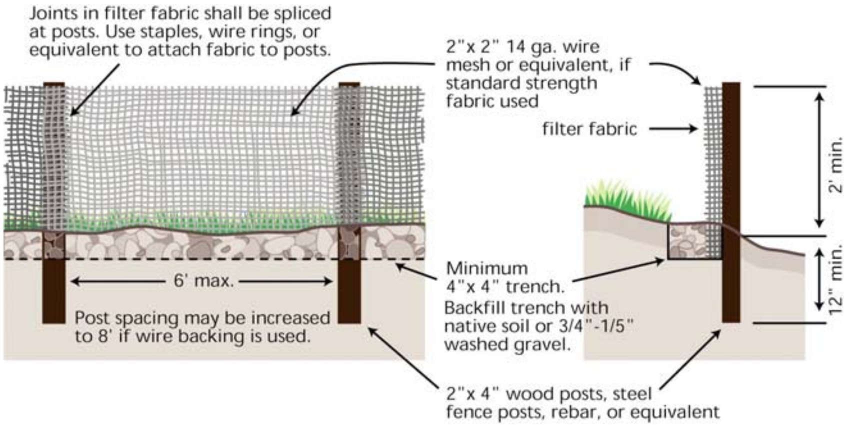


Figure 9.3: Silt fence installation guidelines. *Erosion control measures must be installed properly.*
Source: King County, Washington.

Water Quality

Although sediment is the major source of water quality impairment on construction sites, it is not the only source. Motorized vehicles and equipment or improperly stored containers can leak petroleum products. Vehicles should be steam-cleaned off site on a regular basis and checked for antifreeze leaks and repaired. (Wildlife can be attracted to the sweet taste of most antifreeze and poisoned.) Various other chemicals such as fertilizers and pesticides can be washed off by rain. Most of these problems can be minimized or avoided entirely by thoughtful siting storage areas for chemicals and equipment and staging areas. Gradients should not favor rapid overland flow from these areas into adjacent streams and wetlands. Distances should be as great as possible and the intervening vegetation as dense as site traffic will allow.

Occasionally, implementation activities will require the entry or crossing of heavy equipment into the stream channel (**Figure 9.5**). Construction site planning and layout should always seek to avoid these intrusions. When these intrusions are absolutely necessary, they should be infrequent. Gravelly streambeds are best able to receive traffic; finer substrates should be reinforced with a geoweb network back-

Figure 9.5: Heavy equipment. *Avoid heavy equipment in stream channels unless absolutely necessary.*

filled with gravel. In addition, any equipment used in these activities should be thoroughly steam-cleaned prior to stream entry.

Application of fertilizers and pesticides can also be a source of pollution into water bodies, and their use may be closely regulated in restoration settings. Where their use is permitted, the site manager should closely monitor the quantity applied, the local wind conditions, and the likelihood of rainfall. Potential water quality impacts are a function of the characteristics of the selected pesticide, its form, mode of application, and soil conditions. Pesticides and fertilizers must be stored in a locked and protected storage unit that provides adequate protection from leaks and spills. Pesticides must be prepared or mixed far from streams and, where possible, off site. All containers should be rinsed and disposed of properly.

Air Quality

Air quality in the vicinity of a restoration site can be affected by vehicle emissions and dust. Rarely, however, will either be a major concern during implementation activities. Vehicle emissions are regulated at the source (the vehicle), and dust is usually associated primarily with haul roads or major earthmoving during dry periods. The need for dust control should be evaluated during initial restoration implementation and road planning (if not previously determined during the planning phase of the restoration initiative). Site conditions, duration of construction activities, prevailing winds, and proximity to neighbors should be considered when making decisions on dust control. Temporary road surfaces or periodic water spraying of the road surface are both effective in controlling dust. Covered loads and speed limits on all temporary roads will also reduce the potential for construction-related dust and debris leaving the site (Hunt 1993). Where appropriate, use of volunteer labor in lieu of diesel-powered equipment will help to protect air quality in and surrounding the site. Due to safety concerns, it is recommended that volunteers not be used on a site where heavy equipment will also be used.

Cultural Resources

Since stream corridors have been a powerful magnet for human settlement throughout history, it is not uncommon for historic and prehistoric resources to be buried by sediment or obscured by vegetation along stream corridors. It is quite possible to discover cultural resources during restoration implementation (particularly during restoration that requires earth-disturbing activities). (See **Figure 9.6**.)

Prior to implementation, any potential cultural resources should be identified in compliance with section 106 of the National Historic Preservation Act. An archaeological record search should be conducted during the planning process in accordance with the State Historic Preservation Officer (SHPO). If a site is uncovered unexpectedly, all activity that might adversely affect the historic property must cease, and the responsible agency official must notify the U.S. Department of the Interior (USDI) National Park Service and the SHPO. Upon notification, the SHPO determines whether the activity will cause an irreparable loss or degradation of significant data. This might require on-site consultation with a 48-hour response time for determining significance and appropriate mitigation actions so as not to delay implementation activities inordinately.

If the property is determined not to be significant or the action will not be adverse, implementation activities may continue after documenting consultation findings. If the resource is significant and the on-site activity is determined to be an adverse action that cannot be avoided, implementation activities are delayed until appropriate actions can be taken (i.e., detailed survey, recovery, protection, or preservation of the cultural resources). Under the Historical and Archaeological Data Preservation Act of 1974, USDI may assume liability for delays in implementation.

Noise

Noise from restoration sites is regulated at the state or local level. Although criteria can vary widely, most establish reasonable and fairly consi-

Figure 9.6: Archaeological site. *Cultural resources, such as those at this site in South Dakota, are commonly found near streams.*

stent standards.

The U.S. Housing and Urban Development (HUD) agency has set a maximum acceptable construction noise emission of 65 A-weighted decibels (dBA) at the property line. Numerous studies conducted since the late 1960s suggest that community complaints rise dramatically above 55 dBA (Thumann and Miller 1986). Meeting the HUD standard (65 dBA) requires that typical construction equipment be over 300 feet away from the listener; avoiding the chance of any significant complaints requires about 500 feet of separation or more. The project manager should contact surrounding neighbors prior to restoration implementation. Public awareness of and appreciation for the project goals help improve tolerance for off-site noise impacts. (Impacts from noise on equipment operators is usually not significant since most construction equipment meets the noise standards imposed by the U.S. General Services Administration of 75 dBA at 50 feet.)

High noise levels might be a concern to wildlife as well, particularly during the breeding season. Any sensitive species that inhabit the project vicinity should be identified and appropriate actions taken to reduce noise levels that could adversely affect these species.

Solid Waste Disposal

Debris is an inevitable by-product of implementation activities. The management of debris is a matter of job site safety, function, and aesthetics. From the first day, the locations of equipment storage, vehicle unloading, stockpiled materials, and waste should be identified. At the end of each workday, all scattered construction debris, plant materials, soil, and tools should be gathered up and brought to their respective holding areas. The site should be left as neat and well organized as possible at the end of each day. Even during the workday, sites in close proximity to business or residential districts should be kept as well organized and "sightly" as possible to avoid complaints and delays initiated by unhappy neighbors.

The importance of these measures to the safety and efficiency of the restoration effort as a whole is sometimes evident only to the project manager. Under such conditions, achieving adequate job site cleanliness is almost impossible because the manager alone does not have time to tidy up trash and debris. Meetings with work crews to emphasize this element of the work should occur early in the construction process and be repeated as often as required. People working on site, whether contractors, volunteers, or government personnel, need to be reminded of these needs as an unavoidable part of doing their jobs.

Worksite Sanitation

Sanitation facilities for work crews should be identified before construction begins. Particularly in remote areas, the temptation to allow ad hoc arrangements will be high. In urban areas, the existing facilities of a neighboring business might be offered. In most settings, however, one or more portable toilets should be provided and might be required by local building or grading permits. Although normally self-contained, any facilities should be located to minimize the risk of contamination of surface water bodies by leakage or overflow.

Obtaining Appropriate Equipment

Standard earthmoving and planting equipment is appropriate for most restoration work. Small channels or wetland pool areas can be excavated with backhoes or track-mounted excavators or trackhoes. Trackhoes are mobile over rough or steep terrain (**Figure 9.7**). They have adequate reach and power to work at a distance from the stream channel; with an opposing "thumb" on the bucket, they can maneuver individual rocks and logs with remarkable precision. Logs can also be placed by a helicopter's cable. Although the hourly rate is about that of the daily cost of ground-based equipment, the ability to reach a stream channel without use of an access road is sometimes indispensable.

Where access is good but the riparian corridor is intact, instream modifications can be made with a telescoping crane. This equipment comes in a variety of sizes. A fairly large, fully mobile unit can extend across a riparian zone 100 feet wide to deliver construction materials to a waiting crew without disturbing the intervening ground or vegetation. Where operational constraints permit their use, bulldozers and scrapers can be very useful, particularly for earthmoving activities that are absolutely necessary to get the job done. In addition, loaders are excellent tools for transporting rocks, transplanting large plants, and digging and placing sod.

For planting, standard farm equipment, such as tractors with mounted disks or harrows, are generally suitable unless the ground is extremely wet and soft. Under these circumstances, light-tracking equipment with low-pressure tires or rubber tracks might work. Seeds planted on restoration sites are commonly broadcast by hydroseeding, requiring a special tank truck with a pump and nozzle for spraying the mixture of seeds, fertilizer, binder, and water (**Figure 9.8**). A wider range of seed species can be planted more effectively with a seed drill towed behind a tractor (e.g., Haferkamp et al. 1985).

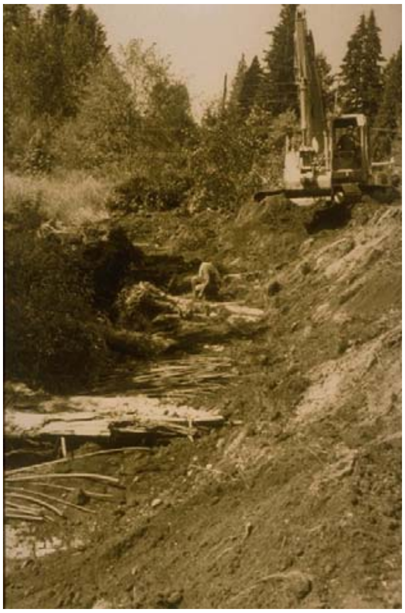


Figure 9.7: Backhoe in operation at a restoration site. *Backhoes are mobile in rough terrain and can move rocks and logs with remarkable precision.*
Source: M. Landin.

Figure 9.8: Hydroseeding of a streambank. *Special tank trucks carrying seed, water, and fertilizer can be used in revegetation efforts.*

Where access is limited, hand planting or aerial spreading of seeds might be feasible.

Site Clearing

Once the appropriate construction equipment has been acquired and site preparation has been completed, any necessary site clearing can begin. Site clearing involves setting the geographic limits, removing undesirable plant species, addressing site drainage issues, and protecting and managing desirable existing vegetation.

Geographic Limits

Site clearing should not proceed unless the limits of activity have been clearly marked in the field. Where large trees are present, each should be marked with colored and labeled flagging to ensure that the field crew understands what is to be cut and what is to remain and be protected from damage.

Removal of Undesirable Plant Species

Undesirable plant species include non-native and invasive species that might threaten the survival of native species. Undesirable plants are normally removed by mechanical means, but the specific method should be tailored to the species of concern if possible. For example, simply cutting the top growth might be adequate management for some plants, but others might resprout rapidly. Where herbicides are selected (and permitted), their use might need to precede clearing of the top growth by up to 2 weeks to allow full absorption of certain chemicals used for this purpose.

For initial brush removal, a variety of track-mounted and towed equipment is available. Bulldozers are most commonly used because of their ready availability, but other equipment can often work more rapidly or more effectively with minimal site disturbance.

Hand clearing with portable tools might be the only appropriate method in some sensitive or difficult areas.

Drainage

Sites that are very wet and poorly drained might require extra preparation. However, many of the traditional efforts to improve drainage are in partial or direct conflict with wetland-protection regulations and might conflict with the restoration goals of the project as a whole. Standard engineering approaches should be reviewed for appropriateness, as well as the timing and schedule of the restoration activities.

Specific techniques for improving the workability of a wet construction site depend on the particular access, storage needs, and site characteristics. Load-bearing mats can provide stable areas for equipment and the unloading of plant materials. Surface water may be intercepted above the working area by a shallow ditch and temporarily routed around the construction area. Subsurface water can sometimes be intercepted by a perforated pipe set in a shallow trench, such as a French drain, but the topography must be favorable to allow positive drainage of the pipe to a surface outlet.

Protection and Management of Existing Vegetation

Protecting existing vegetation on a restoration site requires a certain degree of attention and advanced planning. An area on a site plan that is far from all earthmoving activity might appear to the site foreman as the ideal location for parking idle equipment or stockpiling excess soil. Only a careless minute with heavy equipment, however, can reduce a vegetated area to churned earth (**Figure 9.9**). Vegetation designed for a protection zone should be clearly marked in the field.

Existing vegetation might also require temporary protection if it occupies a part of the site that will be worked, but only late in the implementation sequence. Before that time, it is best left undisturbed to improve the level of overall erosion control. To save mobilization costs, most earthmoving contractors normally begin construction by clearing every part of the site

Figure 9.9: Lessons to be learned. *Heavy equipment can quickly reduce a vegetated area to churned earth.*

that will eventually require it. If clearing is to be phased instead, this requirement must be specified in the contract documents and discussed at a preimplementation meeting.

When identifying and marking vegetation protection zones, the rooting extent of the vegetation should be respected. Fencing and flagging of protected vegetation should be sturdy and maintained. Despite the cool shade and fencing, vegetation protection zones are neither a picnic area nor a storage/staging area. They are zones of no disturbance.

When working in riparian corridors with mature conifers, it is especially important to protect them from mechanical operations which can cause severe damage.

Installation and Construction

Following site preparation and clearing, restoration installation activities such as earthmoving, diversion of flow, and the installation of plant materials can proceed.

Earthmoving

Fill Placement and Disposal

How and where fill is placed on a site should be determined by the final placement of restoration measures. Fills adjacent to retaining walls or similar structures need to meet the criteria for structural fill.

Where plants will be the final treatment of a fill slope, the requirements for soil materials and compaction are not as severe. Loose soil on a steep slope is still prone to erosion or landsliding, however. Where fill is to be placed on slopes steeper than about 2:1, a soils engineer should determine whether any special measures are appropriate (**Figure 9.10**). Even on gentler slopes, surface runoff from above should not be allowed to saturate the new material since the stability of noncompacted fills is generally quite low.

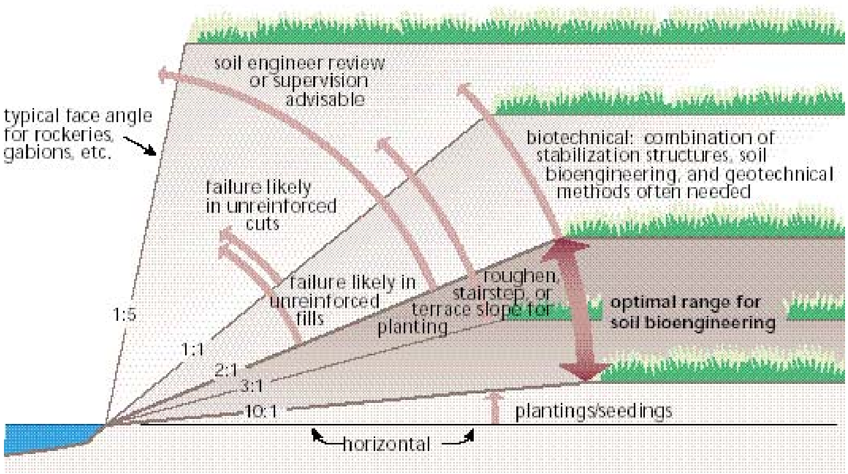


Figure 9.10: ***Treatment of cuts and fills.*** *Slope gradient is an important factor in determining appropriate restoration measures.*

To reduce grading expenses, the cut and fill should be balanced so no material needs to be transported to or from the site. If the volume of material resulting from cuts exceeds that from fills, some of the soil must be disposed of off-site. Disposal sites can be difficult to locate and might require an additional grading permit from the local jurisdiction. These possibilities should be planned for far enough in advance to avoid unanticipated delays during implementation.

As a general rule, topsoil removed from the site should be properly stockpiled for reuse during the final stages of implementation. Even if undesirable species are present, the topsoil will provide a growth medium suitable for the plant community appropriate to the site. It will also be a source of native species that can reestablish the desired diversity most rapidly (Liebrand and Sykora 1992). Stockpiled soil also can be vegetated with species that will be used at the restoration site to protect the soil from erosion and noxious weeds.

Contouring

The erosive power of water flowing down a slope should be recognized during earthmoving. The steepest direction down a hillside is also the direction of greatest erosion by overland or channelized flow. The overall topography of the graded surface should be designed to minimize the uncontrolled flow of runoff in this direction. Channelized flow should be diverted to ditches cut into the soil that more closely follow the level contours of the land. Dispersed sheet flow should be broken up by terraces or benches along the slope that also follow topographic contours. On a fine scale, the ground surface can be roughened by the tracks of a bulldozer driven up and down the slope, or by a rake or harrow pulled perpendicularly to the slope. In either case, the result is a set of parallel ridges, spaced only a few inches apart, that follow the contours of the land surface and greatly reduce on-site erosion.

Final Grading

Earthmoving should result in a slope that is stable, minimizes surface erosion by virtue of length and gradient, and provides a favorable environment for plant growth. The first two criteria are generally determined by plans and can be modified only minimally by variations in grading techniques. Where plans specify a final slope gradient steeper than about 1:1, however, vegetation reestablishment will be very difficult, and a combination of stabilization structures, soil bioengineering, and geotechnical methods will probably be necessary. The shape at the top of the slope is also impor-

Earthmoving should result in a slope that is stable, minimizes surface erosion by virtue of length and gradient, and provides a favorable environment for plant growth.

tant: if it forms a straight abrupt edge, plant regrowth will be nearly impossible. A rounded edge that forms a gradual transition between upland and slope will be much more suitable for growth (Animoto 1978).

Providing a favorable environment for plant growth requires attention to the small-scale features of the slope. Rough-textured slopes, resulting from vehicle tracks or serrated blades, provide a much better environment for seedlings than do smooth-packed surfaces (**Figure 9.11**). Small terraces should be cut into slopes steeper than about 3:1 to create sites of moisture accumulation and enhanced plant growth. Compaction by excessive reworking from earthmoving equipment can result in a lower rate of rainfall infiltrating the soil and, consequently, a higher rate of erosive surface runoff. The result is a loss of the topsoil needed to support plant growth and less moisture available for the plants that remain.

Diversion of Flow

Channelized flow (from stream channels, ditches, ravines, or swales) might need to be diverted, impounded, or otherwise controlled during implementation of restoration measures. In some cases, this need might be temporary, until final grading is complete or plantings have become established. In other cases, the diversion is a permanent part of the restoration. Permanent facilities frequently replace temporary measures at the same location but are often constructed of different materials.

Temporary dikes, lined or grassed water-ways, or pipes can be used to divert channelized flow. Runoff can also be impounded in ponds or sediment basins to allow sediment to settle out.

Most temporary measures are not engineered and are constructed from materials at hand. Dikes (ridges of soil up to a few feet high) are compacted to achieve some stability and are sometimes armored to resist erosion. They are used to keep water from washing over a newly graded or planted slope where erosion is otherwise likely, and to divert runoff into a natural or artificial channel. The loosened soil from swales can be readily compacted into an adjacent dike, improving the efficiency and capacity of the runoff diversion. Pipes or rock-lined ditches can carry channelized water down a slope that is steep enough to otherwise suffer erosion; they can also be used to halt erosion that has already occurred from uncontrolled discharges. Flexible plastic pipe is most commonly used in these situations, although the outlet must be carefully located or well armored with rocks or sandbags to avoid merely shifting the point of erosion farther down-slope.

Sediment ponds and traps are basins either dug into the soil with a rock-armored overflow or impounded by an embankment with an outlet. A fraction of the sediment carried by the site runoff will settle out in the trap, depending on the ratio of surface area or storage volume to inflow rate. The utility of sediment ponds may be limited depending on the sediment-trapping efficiency. A sediment pond can also release nearly as much sediment as is ultimately trapped if the pond is not built to handle maximum surface water flows or is not maintained properly.

Several techniques are available where the active streamflow must be temporarily isolated from installation activities. Most common are temporary dams, constructed of sandbags, geotextile fences, water control structures, or sheet piles. All may be suitable in certain situations, but have drawbacks. Sandbags are inexpensive, but submerged burlap sacks rot quickly and the sand used to fill them might not be appropriate for the stream. Fabric fences can be used in conjunction with sand-bags, but they will not withstand high flows. Water control structures, such as long water-filled tubes available commercially, can be very effective, but need ample lateral space and carry a high initial cost. They also can be swept away by high flows. Sheet piles are effective if heavy equipment is already on site, but their installation and removal can mobilize much fine sediment.

Alternatively, water can be diverted into a bypass pipe, normally made of large flexible plastic (unless anticipated discharges are very great), and the construction area can be kept totally and reliably dry. A dam must be constructed at the pipe inlet to shunt the water, and an adequate apron of nonerosive material must be provided at the discharge. Both of these structures can themselves lead to instream damage, but with care the problems are only temporary. Since fish passage and migration are generally precluded with such a diversion, its applicability is limited.

In some situations unexpectedly erosive conditions will demand better outlet or channel protection than that originally specified in the plans. Erosion control in these settings might require a thick blanket of angular rocks and geotextiles (cloth, plastic grids, or netting) used with plantings. New types of geotextiles are becoming widely available and can serve a wide range of flow conditions. Where possible, channels and spillways should be stabilized using soil bioengineering or other appropriate techniques.

Installation of Plant Materials

Plant establishment is an important part of most restoration initiati-

Figure 9.11: Track-roughened area. *Rough-textured slopes provide a much better environment for seedlings than do smooth-packed surfaces.*

Plant establishment is an important part of most restoration initiatives that require active restoration.

ves that require active restoration. Detailed local standards and specifications that describe planting techniques and establishment procedures should be developed. Native species should be used where possible to achieve the restoration goals. Vegetation can be installed by seeding; planting vegetative cuttings; or using nursery-grown bare-rooted, potted, and burlap-wrapped specimens. If natural colonization and succession is appropriate, techniques may include controlling exotic species and establishing an initial plant community to hasten succession.

Timing

The optimum conditions for successful plant installations are broad and vary from region to region. As a general rule, temperature, moisture, and sunlight must be adequate for germination and establishment. In the eastern and mid-western United States, these conditions are met beginning in late winter or early spring, after ground thawing, and continuing through mid-autumn. In the West, the typical summertime dryness normally limits successful seedings to late summer or early autumn. Where arid conditions persist through most of the year, plants and seedings must take advantage of whatever rainfall occurs, typically in late autumn or winter, or supplemental irrigation must be provided. Because the requirements can vary so much for different species, the local supplier or a comprehensive reference text (e.g., Schopmeyer 1974, Fordham and Spraker 1977, Hartmann and Kester 1983, Dirr and Heuser 1987) should be consulted early in the restoration design phase. If rooted stock is to be propagated from seed before it is planted at the restoration site, 1 to 2 years (including seed-collection time) should be allowed.

Plants should be installed when dormant for the highest rate of survival. Survival is further influenced by species used and how well they are matched to site conditions, available moisture, and time of installation. In mild climates, the growth of roots occurs throughout the winter, improving survival of fall plantings. Where high wintertime flows are anticipated, however, first-season cuttings might not survive unless given some physical protection from scour. Alternatively, planting can occur in the spring before dormancy ends, but supplemental irrigation might be needed even in areas of abundant summertime rainfall. Irrigation might be necessary in some regions of the country to ensure successful establishment of vegetation.

Acquisition

Native plant species are preferred over exotic ones, which might result in un-foreseen problems. Some plant materials can be obtained from commercial sources, but many will need to be collected. When attempting to restore native plant communities, it is desirable to use appropriate genotypes. This requires the collection of seeds and plants from local sources. Early contact with selected sources of rooted stock and seed can ensure that appropriate species in adequate quantities will be available when needed.

The site itself might also be a good source of salvageable plants. Live cuttings can be collected from healthy native vegetation at the donor site. Sharp, clean equipment must be used to harvest the plant material. Vegetation is normally cut at a 40 to 50 degree angle using loppers, pruners, or saws. If the whole plant is being used, the cut is made about 10 inches above the ground, which encourages rapid regeneration in most species. Cuttings typically range from 0.4 to 2 inches in diameter and 2 to 7 feet long.

After harvesting, the donor site should be left in a clean condition. This will avoid the potential for landowner complaints and facilitate potential reuse of the site at some time in the future. Large unused material can be cut for firewood, piled for wildlife cover, or scattered to hasten decomposition. Any diseased material should be burned, per local ordinances.

Transportation and Storage

The requirements for the transport and storage of plant materials vary, depending on the type of material being used. Depending on species, seeds may require a minimum period of dormancy of several weeks or months, with specific temperature requirements during that time. Some seeds may also require scarifying or other special treatment. Nurseries that specialize in native plants are recommended because they should be cognizant of any special requirements. Although the necessary information for any chosen species should be readily available from local seed sources or agricultural extension offices, this interval must be recognized and accounted for in the overall implementation schedule.

Live cuttings present rather severe limitations on holding time. In most cases, they should be installed on the day they are harvested, unless refrigerated storage areas are secured. Thus, donor sites must be close to the restoration site, and access and transportation must be orchestrated to coincide with the correct stage of construction. Live cuttings should be tied in manageable bundles, with the cut ends all lying in the same direction. Since drying is the major threat to survival at this stage, cuttings should be covered with damp burlap during transport and storage (**Figure 9.12**). They should always be shaded from direct sun. On days with low humidity and temperatures above 60 degrees Fahrenheit, the need for care and speed is particularly great. Where temperatures are below this level, "day-after" installation is acceptable, although not optimal. Any greater delay in installation will require refrigeration, reliably cold weather on site, or storage in water.

Rooted stock is also prone to drying, particularly if pots or burlap-wrapped roots are exposed to direct sun. Submergence of the roots in water is not recommended for long periods, but 1 to 2 hours of immersion immediately prior to planting is a common practice to ensure the plant begins its in-place growth without a moisture deficit. On-site storage areas should be chosen with ample shade for pots. Bare-

Figure 9.12: Live cuttings covered with damp burlap to prevent drying during transport. *Drying is a major threat to survival of live cuttings during transport and storage.*

rooted or burlap-wrapped stock should be heeled into damp ground or mulch while awaiting final installation.

Planting Principles

The specific types of plants and plant installations are generally specified in the construction plans and therefore will have been determined long before implementation. A project manager or site foreman should also know the basic installation principles and techniques for the area.

The type of soil used should be determined by the types of plants to be supported. Ideally, the plants have been chosen to match existing site conditions, so stockpiled topsoil can be used to cover the plant material following layout. However, part of the rehabilitation of a severely disturbed site might require the removal of unsuitable topsoil or the import of new topsoil. In these situations, the requirements of the chosen plant species should be determined carefully and the soil procured from suitable commercial or field sites that have no residual chemicals and undesirable plant species.

When using seeds, planting should be preceded by elimination of competing plants and by preparation of the seedbed (McGinnies 1984). The most common methods of seeding in a restoration setting are hand broadcasting and hydroseeding. Hydroseeding and other methods of mechanical seeding might be limited by vehicular access to the restoration site.

When using either cuttings or rooted stock, the soil and the roots must make good contact. This requires compaction of the soil, either by foot or by equipment, to avoid air pockets. It also requires that the soil be at the right moisture content. If it is too dry (a rare condition), the soil particles cannot "slip" past each other to fill in voids. If it is too wet (far more common, especially in wetland or riparian environments), the water cannot squeeze out of the soil rapidly enough to allow compaction to occur.

Another aspect to consider is that quite frequently after planting, the resulting soil is too rough and loose to support vigorous seed growth. The roughness promotes rapid drying, and the looseness yields poor seed-to-soil contact and also erratic planting depths where mechanical seed drills are used. As a result, some means of compaction should be employed to return the soil to an acceptable state for planting.

Special problems may be encountered in arid or semiarid areas (Anderson et al. 1984). The salt content of the soil in these settings is critical and should be tested before planting. Deep tillage is advisable, with holes augured for saplings extended to the water table if at all possible. First-year irrigation is mandatory; ongoing fertilization and weeding will also improve survival.

Competing Plants

Although a well-chosen and established plant community should require no human assistance to maintain vigor and function, competition from other plants during establishment might be a problem. Competing plants commonly do not provide the same long-term benefits for stability, erosion control, wildlife habitat, or food supply. The restoration plan therefore must include some means to suppress or eliminate them during the first year or two after construction.

Competing plants may be controlled adequately by mechanical means. Cutting the top growth of competing plants can slow their development long enough for the desired plants to become established. Hand weeding is also very effective, although it is usually feasible only for small sites or those with an ongoing source of volunteer labor.

Unfortunately, some species can survive even the most extreme mechanical treatment. They will continue to reemerge until heavily shaded or crowded out by dense competing stands. In such cases the alternatives are limited. The soil containing the roots of the undesired vegetation can be excavated and screened or removed from the site, relatively mature trees can be planted to achieve near-instantaneous shading, or chemical fertilizers or herbicides can be applied.

Use of Chemicals

In situations where mechanical controls are not enough, the application of fertilizers and the use of herbicides to suppress undesirable competing species may be necessary.

Herbicides can eliminate undesirable species more reliably, but they may eliminate desirable species. Their use near watercourses may also be severely curtailed by local, state, and federal permit requirements. Several herbicides are approved for near-stream use and degrade quickly, but their use should be considered a last resort and the effects of excessive spray or overspray carefully controlled.

If herbicide use is both advisable and permitted, the specific choice is based first on whether the herbicide is absorbed by the leaves or by the roots (e.g., Jacoby 1987). The most common foliar-absorbed herbicide is 2,4-D, manufactured by numerous companies and particularly effective on broadleaf weeds and some shrubs. Other foliar herbicides have become available more recently and are commonly mixed with 2,4-D for broad-spectrum control. Root-absorbed herbicides are

Since herbicides and fertilizers may be problematic near surface-water, they should be used only if other alternatives are not available.

Table 9.1: Types of mulches.

Mulch	Benefits	Limitations
Chipped wood	Readily available; inexpensive; judged attractive by most	High nitrogen demand; may inhibit seedlings; may float offsite in surface runoff
Rock	May be locally available and inexpensive	Can inhibit plant growth; adds no nutrients; suppresses diverse plant community; high cost where locally unsuitable or unavailable
Straw or hay	Available and inexpensive; may add undesirable seeds	May need anchoring; may include undesirable seeds
Hydraulic mulches	Blankets soil rapidly and inexpensively	Provides only shallow-rooted grasses, but may out compete woody vegetation
Fabric mats	Relatively (organic) or very (inorganic) durable; works on steep slopes	High costs; suppresses most plant growth; inorganic materials harmful to wildlife
Commercial compost	Excellent soil amendment at moderate cost	Limited erosion-control effectiveness; expensive over large areas

either sprayed (commonly mixed with dye to show the area of application) or spread in granular form. They persist longer than most foliar herbicides, and some are formulated to kill newly sprouted weeds for some time after application. Since herbicides and fertilizers may be problematic near surface water, they should be used only if other alternatives are not available.

Mulches

Mulching limits surface erosion, suppresses weeds, retains soil moisture, and can add some organic material to the soil following decomposition. A variety of mulches are available with different benefits and limitations, as shown in **Table 9.1**.

Organic mulches, particularly those based on wood (chips or sawdust), have a high nitrogen demand because of the chemical reactions of decomposition. If nitrogen is not supplied by fertilizers, it will be extracted from the soil, which can have detrimental effects on the vegetation that is mulched. Certain species of wood, such as redwood and cedar, are toxic to certain species of seedlings and should not be used for mulch.

Straw is a common mulch applied on construction and revegetation sites because it is inexpensive, available, and effective for erosion control. Appropriate application rates range from about 3,000 to 8,000 lb/acre. Straw can be spread by hand or broadcast by machine, although uniform application is difficult in windy conditions. Straw must be anchored for the same reason: it is easily transported by wind. It can be punched or crimped into the soil mechanically, which is rapid and inexpensive, but requires high application rates. It can be covered with jute or plastic netting, or it can be covered with a sprayed tackifier (usually asphalt emulsion at rates of about 400 gal/acre).

Straw or hay can also be a source of undesirable weed seed and should be inspected prior to application.

Wood fibers provide the primary mechanical protection in hydraulic mulches (usually applied during hydroseeding). Rates of 1 to 1.5 tons/acre are most effective. They can also be applied as the tackifier over straw at about one-third the above rate. Hydraulic mulches are adequate, but not as effective as straw, for controlling erosion in most settings. However, they can be applied on slopes steeper than 2:1, at distances of 100 feet or more, and in the wind. On typical earthmoving and construction projects, they are favored because of the speed at which they can be applied and the appearance of the resulting slope—tidy, smooth, and faintly green. The potential drawbacks—introducing fertilizers and foreign grasses that are frequently mixed into hydraulic mulches—should be carefully evaluated.

An appropriate mulch in many restoration settings is a combination of straw and organic netting, such as jute or coconut fibers (**Figure 9.13**). It is the most costly of the commonly used systems, but erosion control and moisture retention are highly effective, and the problems with undesirable seeds and excess fertilizers are reduced. The value of an effective mulch to the final success of an initiative is generally well in excess of its cost, even when the most expensive treatment is used.

Figure 9.13: A well-mulched site. *Mulching is an effective method for improving the final outcome of stream corridor restoration.*

The value of an effective mulch to the final success of an initiative is generally well in excess of its cost, even when the most expensive treatment is used.

Irrigation

In any restoration that involves replanting, the need for irrigation should be carefully evaluated. Irrigation might not be needed in wetland and near-stream riparian sites or where rainfall is well distributed throughout the year. Irrigation may be essential to ensure success on upland sites, in riparian zones where seasonal construction periods limit installation to dry months, or where a wet-weather planting may have to endure a first-year drought. Initial costs are lowest with a simple overhead spraying system. Spray systems, however, have inefficient water delivery and have heightened potential for vandalism. Drip-irrigation systems are therefore more suitable at many sites (Goldner 1984). There is also a greater potential for undesirable species with spray irrigation since the area between individual plants receives moisture.

Fencing

If the plant species chosen for the site are suitable, little or no special effort will be necessary for survival and establishment. During the initial construction and postconstruction phases, however, plants will commonly need some measure of physical protection. Construction equipment, work crews, onlookers, grazing horses and cattle, and browsing deer and other herbivores can reduce a new plant installation to barren or crushed twigs in very short order. Vandalism is also a potential problem in populated areas. Fencing is an effective, low-cost method to provide physical protection from these types of hazards and should be included in virtually any restoration.

The type of fencing should be chosen for the type of hazard anticipated. Inexpensive, fluorescent orange plastic fencing is very effective for controlling people and equipment during construction, but it rarely makes a suitable long-term barrier. Domestic cattle can be controlled by a variety of wood and wire fences (**Figure 9.14**). Depending on the density of grazing animals, these fences are best assumed to be permanent installations and their design chosen accordingly. Electric fences can also be effective, and the higher cost of the electrification equipment can be offset by lower costs for materials and installation. Where deer are a known problem, fencing must be robust, but it probably will not need to remain in place permanently after well-chosen plants have matured. Damage from small mammals may be halted with chicken wire alone, surrounding individual saplings, or below-ground collars. Individual wire cages or other control devices might be necessary to protect trees.

Inspection

Frequent, periodic inspection of work, whether done by a landowner, contractor, volunteer group, or government personnel, is mandatory. Defects such as poor planting methods, stressed plant materials, inadequate soil compaction, or sloppy erosion control, may become evident only weeks or months after completion of work unless the activities on the site are regularly reviewed. Some of those activities may require specialized testing, such as the degree of compaction of a fill slope. Most require little more than observations by an inspector familiar with all elements of the design.

In the case of contracted work, it is the responsibility of the construction inspector to monitor installation activities to ensure that the contractor completes work according to the contract plans and specifications. At key points during construction, the inspector should consult with clients and design team(s) for assistance. The inspector should create comprehensive documentation of the construction history in anticipation of any future audit or quantity dispute. All inspections should result in a written record that includes at least the information shown in **Figure 9.15**.

Daily and weekly reports are invaluable to maintain clear communication about billable days, progress, and anticipated problems. These written reports establish the authority to release payment to the contractor and provide the main documentation in case of a dispute between the client and contractor. Completeness, timeliness, and clarity of documentation are critical.

Inspection of restoration elements that involve management actions (i.e., land-use controls, grazing restrictions, etc.) require follow-up communication with the resource manager or landowner. A review of the action again-

Figure 9.14: A permanent livestock fence. *Fencing is an effective, low-cost method of providing physical protection to restoration sites.*

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Figure 9.15: Sample of an inspector's daily report. *Frequent, periodic inspection is a mandatory part of restoration implementation.*

st the plan and applicable standards should be conducted. For example, rotational grazing may be a critical plan element to achieve restoration of the stream corridor. Inspection of this plan element would involve a review of the rotation scheme, condition of individual pastures or ranges, and condition of fencing and related watering devices.

Keep in mind that although plans and specifications should be specific to the conditions of the site, they might have been developed from generic sets or from those implemented elsewhere.

On-Site Inspection Following Installation

The final inspection after installation determines the conditions under which the contractor(s) can be paid and the contract finalized. It must occur promptly and should determine whether all elements of the contract have been fulfilled satisfactorily. Before scheduling this final inspection, the project manager and inspector, together with any other necessary members of the restoration team, inspect the work and prepare a list of all items requiring completion by the contractor. This "pre-final" inspection is in fact the most comprehensive review of the work that will occur, so it must be conducted with care and after nearly all of the work has been completed. The final inspection should occur with representatives of both the client and the contractor present after completion of all required work and after site cleanup, but before equipment is removed from the site to facilitate additional work if necessary. It must address removal of protection measures no longer needed, such as silt fences. These are an eyesore and might inhibit restoration. A written report should state the complete or provisional acceptance of the work, the basis on which that judgment has been made, and any additional work that is needed prior to final acceptance and payment.

Follow-up Inspections

Planning for successful implementation should always look beyond the period of installation to the much longer interval of plant establishment. Twelve or more additional site visits are advisable over a period of many months or years. Such inspections will generally require a separate budget item that must be anticipated during restoration planning. If they are included in the specifications, they may be the responsibility of the contractor. A sample inspection schedule is shown in **Table 9.2**. Although this level of activity after installation might seem beyond the scope of a project, any restoration work that depends on the growth of vegetation will benefit greatly from periodic review, particularly during the first two years.

Documentation of follow-up inspections is important, both to justify recommendations and to provide a record from which chronic problems can be identified. Documentation can include standard checklists, survey data, cross sections, data sheets, data summaries, and field notes. Sketches, maps, and permanent photo points can be used to document vegetation development. Videotape can be particularly useful to document the performance of structures during various flows, to illustrate wildlife use and floodplain storage of floodwaters, and otherwise to record the performance and functions of the corridor system.

Table 9.2: Sample inspection schedule.

Time Since Installation	Inspection Interval
2 Months	2 weeks (4 total)
6 Months	1 month (5 total)
2 Years	6 months (3 total)

Inspection reports are primarily intended to address maintenance issues. Problems discovered in the inspection process should be documented in a report that details deficiencies, recommends specific maintenance, and explains the consequences of not addressing the problems. Postplanting inspections to ensure survival require documentation and immediate action. Consequently, the reporting and response loop should be simple and direct so that inspections indicating the need for emergency structural repairs can be reported and resolved without delay.

General Inspection

To the extent feasible, the entire stream corridor should be inspected annually to detect areas of rapid bank erosion or debris accumulation (**Figure 9.16**). A general inspection can also identify inappropriate land uses, such as encroachments of roads near banks or uncontrolled irrigation water returns, that might jeopardize restoration measures, affect water quality, or otherwise interfere with restoration objectives. The integrity of fences, water access, crossings, and other livestock control measures should be inspected (**Figure 9.17**). Lack of compliance with agreed-upon best management practices should be noted as well. Aerial photos are particularly useful in the

Figure 9.16: Flood debris. *The entire corridor should be inspected annually to detect areas of debris accumulation from flood flows.*

Figure 9.17: Fencing. *The integrity of fencing should be inspected periodically.*

overview inspection, but inspections by boat or on foot can be more informative in many cases.

Bank and Channel Structures

Special inspections should be conducted following high flows, particularly after the first flood event following installation. Soil bioengineering measures should be assessed during prolonged drought and immediately after high flows during the first few years following installation until the system is well established.

Most routine inspections of bank and channel measures should be conducted during low-water conditions to allow viewing of the measure as well as channel bed changes that might threaten its future integrity. This is particularly true of bank stabilization works where the principal mechanism of bank failure is undermining at the toe. A low water inspection should involve looking for displaced rock, settling or tilting, undermining, and similar problems (Johnson and Stypula 1993).

In the past, bank stabilization measures were routinely cleared of vegetation to facilitate inspection and prevent damage such as displacement of rock by trees uprooted from a revetment during a flood. However, evidence that vegetation compromises revetment integrity has not been documented (Shields 1987, 1988). Leaving vegetation in place or planting vegetation through rock blankets has been encouraged to realize the environmental benefits of vegetated streambanks. Consequently, agencies have modified inspection and maintenance guidelines accordingly in some areas.

Vegetation

Streambanks that have been stabilized using plantings alone or soil bioengineering techniques require inspections, especially in the first year or two after planting (**Figure 9.18**). It is important that the planted material be checked frequently to ensure that the material is alive and growing satisfactorily. Any dead material should be replaced and the cause of mortality determined and corrected if possible. If the site requires watering, rodent control, or other remedial actions, the problem must be detected and resolved immediately or the damage may become severe enough to require extensive or complete replanting. Competition from weeds should be noted if it is likely to suppress new plantings. If nonnative plants capable of invading and outcompeting native species are known to be present in the area, both plantings and existing native vegetation should be inspected. Any newly established nonnative populations should be eradicated quickly.

After the first growing season, semi-annual to annual evaluations should be sufficient in most cases. At the end of a 2-year period, 50 percent or more of the originally installed plant material should be healthy and growing well (**Figure 9.19**). If not, determining the cause of die-off and subsequent replanting will probably be necessary. If the installation itself is determined to have been improper, any warranty or dispute- resolution clauses in the plant installation contract might need to be invoked.

The effectiveness of bank protection is based largely on the development of the plants and their ability to bind soils at moderate flow velocities. The bank protection measures should be inspected immediately after high-flow events in the first few years, particularly if the plantings have not fully established. Washouts, slumping of geogrids, and similar problems require detection and correction, since they might become the sites of further deterioration and complete failure if left uncorrected.

Floodplain and other off-channel plantings might be important components of the corridor restoration plan as well. Inspection requirements are similar to those on streambank sites but are less critical to the integrity of the project in terms of preventing additional damage. Nevertheless, several site visits are appropriate during the first growing season to detect problems due to browsing, insects, too much or too little water, and other causes. Inspection of plantings that require irrigation during establishment, as well as of the irrigation system, may be needed on a weekly or more frequent basis.

Techniques for inspecting vegetation survival are fairly straightforward. Satisfactory survival rates may be determined using stem counts within sample plots or estimates of cover percentages, depending on the purpose of the plantings. For example, Johnson and Stypula (1993) suggest that woody plantings established for streambank protection should not include open spaces more than 2 feet in dimension. In most cases, such criteria can be established in advance based on common-sense decisions regarding the adequacy of establishment relative to the objectives. Where more detailed monitoring is appropriate to document development of habitat quality or similar objectives, more rigorous monitoring techniques can be used. (See Section 9.B).

Figure 9.18: Revegetation project. *It is important that the planted material be inspected frequently to ensure that it is alive and growing satisfactorily.*

Figure 9.19: Revegetation project, 1 to 2 years postconstruction. *At the end of a 2-year period, 50 percent or more of the original plantings should be healthy and growing well.* Source: King County, Washington.

Urban Features

Stream corridor objectives may require periodic inspections of features other than the stream, streambank, and corridor vegetation. In urban areas, these features may be a major focus of the inspection program. Facilities, nest boxes, trails, roads, storm water systems, and similar features must be inspected to ensure they are in satisfactory condition and are not contributing to degradation of the stream corridor. Access points required to accomplish maintenance and emergency repairs should be checked for serviceability. Popular public use areas, particularly stream access points, should be evaluated to determine whether measures are being damaged, erosion is being initiated, or project objectives are otherwise being impeded. Inspection should reveal whether signs, trail closures, and other traffic-control measures are in place and effective. Trash and debris dumping, off-road vehicle damage, vandalism, and a wide variety of other detrimental occurrences may be noted during routine inspections.

Maintenance

Maintenance encompasses those repairs to restoration measures which are based on problems noted in annual inspections, are part of regularly scheduled upkeep, or arise on an emergency basis.

- *Remedial maintenance* is triggered by the results of the annual inspection (**Figure 9.20**). The inspection report should identify and prioritize maintenance needs that are not emergencies, but that are unlikely to be addressed through normal scheduled maintenance.
- *Scheduled maintenance* is performed at intervals that are preestablished during the design phase or based on project-specific needs. Such maintenance activities as clearing culverts or regrading roads can be anticipated, scheduled, and funded well in advance. In many instances, the scheduled maintenance fund can be a tempting source for emergency funds, but this can result in neglect of routine maintenance, which may eventually produce a new, more costly, emergency.
- *Emergency maintenance* requires immediate mobilization to repair or prevent damage. It may include measures such as replacement of plants that fail to establish in a soil bioengineered bank stabilization, or repair of a failing revetment. Where there is a reasonable probability that repair or replacement might be required (e.g., anything that depends on vegetation establishment), sources of funding, labor, and materials should be identified in advance as part of the contingency planning process. However, there should be some general strategy for allowing rapid response to any emergency.

FAST FORWARD

Preview Section 9.B, Monitoring Techniques Appropriate for Evaluation Restoration.

Many maintenance actions will require permits, and such requirements should be identified well in advance to accommodate permitting delays. Similarly, access to areas likely to require maintenance (e.g., bank stabilization structures) should be guaranteed at the time of construction, and the serviceability of access roads verified periodically.

Various agencies and utilities may have maintenance responsibilities that involve portions of the stream corridor, such as road and transmission line crossings. This work should be coordinated as necessary to ensure there are no conflicts with corridor objectives.

Channels and Floodplains

Corridor restoration that includes reconfiguration of the channel and floodplain may require remedial action if the system does not perform as expected in the first few years after work has been completed. Any repairs or redesign, however, should be based on a careful analysis of the failure. Some readjustment is to be expected, and a continuing dynamic behavior is fundamental to successful restoration. Because establishment of a dynamic equilibrium condition is usually the intent, maintenance should be limited to actions that promote self-sustainability.

Many traditional channel maintenance actions may be inappropriate in the context of stream corridor restoration. In particular, removal of woody debris may be contrary to restoration objectives (**Figure 9.21**). Appropriate levels of woody debris loading should be a design specification of the project, and the decision to remove or reposition particular pieces should be based

Figure 9.20: Remedial maintenance. *Soil bio-engineering used to repair failing revetment.*

Figure 9.21: Accumulated woody debris. *Removal of woody debris may be contrary to restoration objectives.*

on specific concerns, such as unacceptably accelerated bank erosion due to flow deflection, creation of ice jams causing an increased chance for flooding, or concerns about safety in streams with high recreational use. In cases where woody debris sources have been depleted, periodic addition of debris may be a prescribed maintenance activity. (See next page for story on engineered log jams.)

Protection/Enhancement Measures

Measures intended to enhance fish habitat, deflect flows, or protect banks are likely to require periodic maintenance. If failure occurs soon after installation, the purpose and design of the measure should be reevaluated before it is repaired, and the mechanism of failure should be identified. Early failure is an inherent risk of soil-bioengineered systems that are not fully effective until the plants are well rooted and the stems reach a particular size and density. Although a design weakness may be identifiable and should be corrected, more often the mechanism of failure will be that the measure has not yet developed full resistance to high-flow velocities or saturation of bank soils. Replanting should be an anticipated potential maintenance need in this situation.

In many stream corridor restoration areas, the intent of streambank and channel measures is to provide temporary stabilization until riparian vegetation develops and assumes those functions. In such cases, maintenance of some structures might become less important over time, and they might eventually be allowed to deteriorate. They can be wholly or partially removed if they represent impediments to natural patterns of channel migration and configuration, or if some components (cables, stone, geofabrics) become hazards.

Vegetation

Routine maintenance of vegetation includes removal of hazardous trees and branches that threaten safety, buildings, fences, and other structures, as well as maintenance of vegetation along road shoulders, trails, and similar features.

Planted vegetation may require irrigation, fertilization, pest control, and similar measures during the first few years of establishment. In large-scale planting efforts, such as floodplain reforestation efforts, maintenance may be precluded. Occasionally, replanting will be needed because of theft.

Maintenance plans should anticipate the need to replant in case soil-bioengineered bank protection structures are subjected to prolonged high water or drought before the plants are fully established. Techniques using numerous cuttings establish successfully, it might be desirable to thin the dense brush that develops to allow particular trees to grow more rapidly, especially if channel shading is a restoration objective. Often, bank protection measures become popular points for people to access the stream (for fishing, etc.). Plantings can be physically removed or trampled. Replanting, fencing, posting signs, or taking other measures might be needed.

Other Features

A wide variety of other restoration features will require regular maintenance or repair. Rural restoration efforts might require regular maintenance and periodic major repair or replacement of fences and access roads for management and fire control. Public use areas and recreational facilities require up-keep of roads, trails, drainage systems, signs, and so forth (**Figure 9.22**). Maintenance of urban corridors may be intensive, requiring trash removal, lighting, and other steps. An administrative contact should be readily available to address problems as they develop. As the level of public use increases, contracting of maintenance services might become necessary, and administration of maintenance duties will become an increasingly important component of corridor management.

Restoration measures placed to benefit fish and wildlife (e.g., nest boxes and platforms, waterers) need annual cleaning and repair. These maintenance activities can be as time-consuming as the original installation, and structures that are in bad condition might draw public attention and criticism. The maintenance commitment should be recognized before such structures are installed. Special wildlife management units, such as moist-soil-management impoundments and green-tree reservoirs, require close attention to be managed effectively.

Flooding and drawdown schedules must be fine-tuned based on site-specific conditions (Fredrickson and Taylor 1982). Special equipment might be needed to maintain levees, to work on soft ground, to repair drainage structures, and to pump out facilities, all of which might incur substantial fuel costs. The maintenance needs in these kinds of situations require that professional resource managers be on site regularly. Not operating the restoration attentively can create nuisance or hazardous conditions, have severe detrimental effects on existing resources, and fail to produce the desired results.

Figure 9.22: Streamside trail. *Public use areas and recreational facilities require upkeep of roads, trails, and signs.*

Mosquito control may also be a maintenance concern near inhabited areas, particularly if the restoration encourages the development of slackwater areas, such as beaver ponds, backwaters, and floodplain depressions. In some cases, control techniques may directly interfere with restoration objectives, but threats to people and livestock might make them necessary.

9.B Monitoring Techniques Appropriate for Evaluating Restoration

As discussed in Chapter 6, the completion of implementation does not mark the end of the restoration process. Restoration practitioners must plan for and invest in the monitoring of stream corridor restoration. The type and extent of monitoring will depend on specific management objectives developed as a result of stream corridor characterization and condition analysis. Monitoring may be conducted for a number of different purposes including:

- *Performance evaluation:* Assessed in terms of project implementation and ecological effectiveness. Ecological relationships used in monitoring and assessment are validated through collection of field data.
- *Trend assessment:* Includes longer term sampling to evaluate changing ecological conditions at various spatial and temporal scales.
- *Risk assessment:* Used to identify causes and sources of impairment within ecosystems.
- *Baseline characterization:* Used to quantify ecological processes operating in a particular area.

This section examines monitoring from the perspective of evaluating the performance of a restoration initiative. Such initiatives seek to restore the structure and functions discussed in earlier chapters. Designing a monitoring program that directly relates to those valued functions requires careful planning to ensure that a sufficient amount of information is collected. Such monitoring uses measurements of physical, biological, and chemical parameters to evaluate the effectiveness of the restoration and to facilitate adaptive management where needed. Sampling locations, measurements to be made, techniques to be used, and how the results will be analyzed are important considerations in monitoring.

REVERSE

Review previous chapters for an introduction to the restoration of stream corridor structure and functions.

Adaptive Management

The implementation, effectiveness, and validation components of performance monitoring provide a vehicle to determine the need for adaptive management. Adaptive management is the process of establishing checkpoints to determine whether proper actions have been taken and are effective in providing desired results. Adaptive management provides the opportunity for course correction through evaluation and action.

Implementation Monitoring

Implementation monitoring answers the question, "Were restoration measures done and done correctly?" Evaluating the effectiveness of restoration through physical, biological, and/or chemical monitoring can be time-consuming, expensive, and technically challenging. Time and partnerships are needed to build the capability for evaluating project effectiveness based on changes in ecological condition. Therefore, an important interim step to this goal is implementation monitoring. This comparatively simple process of documenting what was done and whether or not it was done properly can yield valuable information that promotes refinement of restoration practices.

Adaptive management provides the opportunity or course correction through valuation and action.

Effectiveness Monitoring

Effective monitoring answers the question "Did restoration measures achieve the desired results?" or more simply "Did the restoration initiative work?" Effectiveness monitoring evaluates success by determining whether the restoration had the desired effect on the ecosystem. Monitoring variables focus on indicators that document achievement of desired conditions and are closely linked with project goals. It is important that indicators selected for effectiveness monitoring are sensitive enough to show change, are measurable, are detectable and have statistical validity. This level of monitoring is more time-consuming than implementation monitoring, making it more costly. To save time and money, monitoring at this level is usually performed on a sample population or portion of a project with results extrapolated to the whole population.

Validation Monitoring

Validation monitoring answers the question "Are the assumptions used in restoration design and cause-effect relationships correct?" Validation monitoring considers assumptions made during planning and execution of restoration measures. This level of monitoring is performed in response to nonachievement of desired results once proper implementation is confirmed. A restoration initiative that fails to achieve intended results could be the result of improper assumptions relative to ecological conditions or selection of invalid monitoring indicators. This level of monitoring is always costly and requires scientific expertise.

CASE STUDY

Engineered Log Jams for Bank Protection and Habitat Restoration

Most riverbank protection measures are not designed to improve aquatic or riparian habitat, and many restoration initiatives lack sufficient engineering and geomorphic analysis to effectively restore natural functions of riparian and aquatic ecosystems. The ecological importance of instream woody debris (WD) has been well documented. Woody debris within a stream can often influence the instream channel structure by increasing the occurrence of pools and riffles. As a result, streams with WD typically have less erosion, slower routing of organic detritus (the main food source for aquatic invertebrates), and greater habitat diversity than straight, even-gradient streams with no debris. Woody debris also provides habitat cover for aquatic species and characteristics ideally suited for fish spawning.

Reintroduction of WD (or log jams) in many parts of the United States has been extensive, but limited understanding of WD stability has hampered many of these efforts. Engineered log jams (ELJs) can restore riverine habitat and in some situations can provide effective bank protection ***(Figure 9.23)****. Although WD is often considered a hazard because of its apparent mobility, research in Olympic National Park has documented that stable WD jams can occur throughout a drainage basin (Abbe et al. 1997). Even in large alluvial channels that migrate at rates of 30 ft./yr, jams can persist for centuries, creating a mosaic of stable sites that in turn host the large trees necessary to initiate stable jams. Engineered log jams are designed to emulate natural jams and can meet management or restoration objectives such as bank protection and debris retention.*

After learning about the uncertainty and potential risks of creating man-made log jams, landowners near Packwood, Washington, decided the potential environmental, economic, and aesthetic benefits outweighed the risks. An experimental project consisting of three ELJs was implemented to control severe erosion along 1,400 ft. of the upper Cowlitz River. The channel at the site was 645 ft. wide and had an average bank erosion rate of 50 ft./yr from 1990 to 1995. Five weeks after constructing the log jams, the project experienced a 20-year recurrence flow (30,000 ft.^{3}/s). Each ELJ remained intact and met design objectives by transforming an eroding shoreline into a local depositional environment (i.e., accreting shoreline). Approximately 93 tons of WD that was in transport during the flood was trapped by the ELJs, alleviating downstream hazards and enhancing structure stability. Improvements in physical habitat included creation of complex scour pools at each ELJ (Abbe et al. 1997).

Landowners have been delighted by the experiment. The ELJs have remained intact, increased in size, and reclaimed some of the formerly eroded property even after being subjected to major floods in February 1996 and March 1997. When compared to traditional bank stabilization methods, which typically employ the extensive use of exotic materials such as rock rarely found in low-gradient alluvial channels, ELJs can offer an effective and low-cost alternative for erosion control, flood control, and habitat enhancement. The cumulative effect of most traditional bank stabilization methods over time results in progressive channel confinement and detachment of the riparian environment from the channel (e.g., loss of streamside vegetation). In stark contrast, the cumulative effects of using ELJs include long-term protection of a significant floodplain, improvement of instream and riparian habitat, and bank stabilization (Abbe et al. 1997).

Comprehensive geomorphic and hydraulic engineering analysis is required to determine the type of WD needed and the appropriate size, position, spacing, and type of ELJ structure for the particular site(s) and project objectives. Inappropriate design and application of ELJs can result in negative impacts such as local accelerated bank erosion, unstable debris, or channel avulsion. Acknowledging the potential risks and uncertainties of ELJs, their use should be limited to well-documented experimental situations. Continued research and development of ELJs involving field application in a variety of physiographic and climatic conditions is needed. ELJs can provide a means to meet numerous objectives in the management and restoration of rivers and riparian corridors throughout the United States.

Fig. 9.23: Engineered log jams. *Engineered log jams (ELJs) can restore riverine habitat and in some situations provide effective bank protection.*

Evaluation Parameters

Physical Parameters

A variety of channel measurements are appropriate for performance evaluation (**Figure 9.24**). The parameters presented in **Table 9.3** should be considered for measurement of physical performance and stability. Stream pattern and morphology are a result of the interaction of eight measurable parameters— width, depth, channel slope, roughness of channel materials, discharge, velocity, sediment loads, and sediment size (Leopold et al. 1964).

These parameters and several other dimensionless ratios (including entrenchment, width/depth ratio, sinuosity, and meander/width ratio) can be used to group stream systems with similar form and pattern. They have been used as delineative criteria in stream classification (Rosgen 1996). Natural streams are not random in their variation.

A change in any of the primary stream variables results in a series of channel adjustments, resulting in alterations of channel pattern and form, and attendant changes in riparian and aquatic habitat.

Biological Parameters

Biological monitoring can cover a broad range of organisms, riparian conditions, and sampling techniques. In most cases, budget and staff will limit the diversity and intensity of evaluation methods chosen. Analytical methods for evaluating biological attributes are discussed in Section 7.D of this document.

Table 9.4 provides examples of the biological attributes of stream ecosystems that may be related to restoration goals. Biological aspects of the stream corridor that may be monitored as part of performance goals include primary productivity, invertebrate and fish communities, riparian/terrestrial wildlife, and riparian vegetation. This may involve monitoring habitat or fauna to determine the degree of success of revegetation efforts or instream habitat improvements.

REVERSE

Review Chapter 7D's section on analytical methods for evaluating biological attributes.

Biological monitoring programs can include the use of chemical measures. For example, if specific stressors within the stream system, such as high water temperatures and low dissolved oxygen, limit biological communities, direct monitoring of these attributes can provide an evaluation of the performance of more intensive remedial practices, including point source pollution reduction.

Chemical Parameters

Monitoring is necessary to determine if a restoration initiative has had the desired effect on water chemistry. The type and extent of chemical monitoring depends upon the goal of the monitoring program. Major chemical parameters of water and their sampling are discussed in Chapters 2 and 7.

A factor in designing a chemical monitoring approach is the amount of change expected in a system. If the restoration goal, for example, is to reduce the salinity in a stream by 5 percent, it would be much more difficult to detect than a goal of reducing salinity by 50 percent.

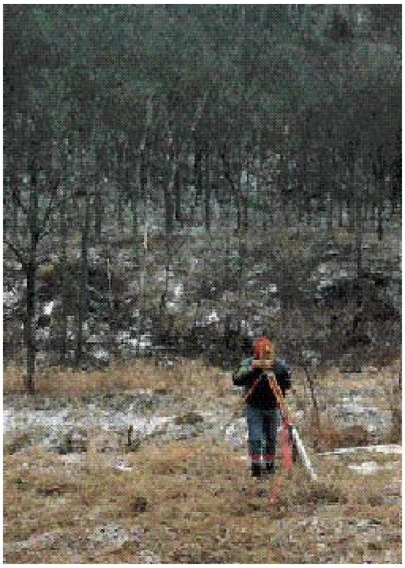

Figure 9.24: Measurement of a stream corridor. *Monitoring the physical aspects of the stream corridor system is important in evaluating the success of any restoration effort.*

REVERSE

Review Chapters 2 and 7 for information on chemical water parameters and their sampling.

Also, review Chapter 8's section on reference reaches.

Chemical monitoring can often be used in conjunction with biological monitoring. There are pros and cons for using chemical and biological parameters when monitoring. Biological parameters are often good integrators of several water quality parameters. Biological indicators are especially useful when determining the bioaccumulation of a chemical.

Water chemistry samples are typically easier to replicate, can disclose slow changes over time, and be used to prevent catastrophic events when chemical characteristics are near toxic levels. For example, water quality monitoring might detect a slow decrease in pH over a period of time. Some aquatic organisms, such as trout, might not respond to this gradual change until the water becomes toxic. However, water quality monitoring could detect the change and thereby avoid a catastrophic event. An ideal monitoring program would include both biological and chemical parameters.

Important chemical and physical parameters that might have a significant influence on biological systems include the following:

- Temperature
- Turbidity
- Dissolved oxygen
- pH
- Natural toxics (mercury) and manufactured toxics
- Flow
- Nutrients
- Organic loading (BOD, TOC, etc.)
- Alkalinity/Acidity
- Hardness
- Dissolved and suspended solids
- Channel characteristics
- Spawning gravel
- Instream cover
- Shade
- Pool/riffle ratio

- Springs and ground water seeps
- Bed material load
- Amount and size distribution of large woody debris (i.e., fallen trees)

These parameters may be studied independently or in conjunction with biological measurements of the ecological community.

Reference Sites

Understanding the process of change requires periodic monitoring and measurement and scientific interpretation of the information as it relates to the stream corridor. In turn, an evaluation of the amount of change attributed to restoration must be based on established reference conditions developed by the monitoring of reference sites. The following are important considerations in reference site selection:

- What do we want to know about the stream corridor?
- Are identified sites minimally-disturbed?
- Are the identified sites representative of a given ecological region, and do they reflect the range of natural variability associated with a given stream class?
- What is the least number of sites required to establish reference conditions?
- What are the impediments to reference site access?

Reference sites provide examples of a properly functioning ecosystem. It is from these reference sites that desired conditions are determined and levels of environmental indicators identified. Environmental indicators become the performance criteria to monitor the success of a initiative.

Table 9.3: Physical parameters to be considered in establishing evaluation criteria for measurement of physical performance and stability.

Plan view	Sinuosity, width, bars, riffles, pools, boulders, logs
Cross sectional profiles — by reach and features	Sketch of full cross section
	Bank response angle
	Depth bankfull
	Width
	Width/depth ratio
Longitudinal profile	Bed particle size distribution
	Water surface slope
	Bed slope
	Pool size/shape/profile
	Riffle size/shape/profile
	Bar features
Classification of existing streams (all reaches)	Varies with classification system
Assessment of hydrologic flow regimes through monitoring	2-, 5-, 10-year storm hydrographs
	Discharge and velocity of base flow
Channel evolutionary track determination	Decreased or increased runoff, flash flood flows
	Incisement/degradation
	Overwidening/aggradation
	Sinuosity trend—evolutionary state, lateral migration
	Increasing or decreasing sinuosity
	Bank erosion patterns
Corresponding riparian conditions	Saturated or ponded riparian terraces
	Alluvium terraces and fluvial levees
	upland/well-drained/sloped or terraced geomorphology
	Riparian vegetation composition, community patterns and successional changes
Corresponding watershed trends–past 20 years and future 20 years	Land use/land cover
	Land management
	Soil types
	Topography
	Regional climate/weather

Human Interest Factors

Human activities requiring use of a healthy environment may often be important factors for evaluating stream corridor restorations (**Figure 9.25**). In these cases, the ability of the stream

Table 9.4: Examples of biological attributes and corresponding parameters that may be related to restoration goals and monitored as part of performance evaluation.

Biological Attribute	Parameter
Primary productivity	Periphyton
	Plankton
	Vascular and nonvascular macrophytes
Zooplankton/diatoms	
Invertebrate community	Species
	Numbers
	Diversity
	Biomass
	Macro/micro
	Aquatic/terrestrial
Fish community	Anadromous and resident species
	Specific populations or life stages
	Number of outmigrating smolts
	Number of returning adults
Riparian wildlife/terrestrial community	Amphibians/reptiles
	Mammals
	Birds
Riparian vegetation	Structure
	Composition
	Condition
	Function
	Changes in time (succession, colonization, extirpation, etc.)

corridor to support the activity indicates benefits drawn from the stream corridor as well as adding insight into stream ecosystem condition. Many human interest- oriented criteria used in performance evaluations can serve the dual function of evaluating elements of human use and ecological condition together:

- Human health (disease, toxic/fish consumption advisories)
- Aesthetics (odor, views, sound, litter)
- Non-consumptive recreation (hiking, birding, whitewater rafting, canoeing, outdoor photography)

Many human interest-oriented criteria used in performance valuations can serve the dual function of valuating elements of human use and ecological condition together.

Performance Evaluation of Fish Barrier Modifications

Fish barrier modifications provide a good example of a technically difficult performance evaluation. The goal of the restoration is easily understood and stated. Barrier modification provides one of two options—to increase populations (increase upstream and downstream movement) or to decrease populations (restrict movement).

In all cases, the specific target species should be identified. If the goal is to restore historic runs of commercial fishes, data for commercial landings may be available to provide guidance. Habitat models are available for species such as Atlantic salmon and can provide insight into expected carrying capacities of nursery habitat. Existing runs in adjacent or nearby river(s) may be examined for population levels and trends that can provide insight into realistic goals. Barriers may be planned for only short-term protection of some species (e.g., protection against cannibalism) or for longer term exclusion of problematic or undesirable species.

Methodologies to evaluate the success of fish barrier modifications can use a variety of field methods to count the number of adult spawners, to determine the abundance of fry, to estimate the size of the outmigrating juvenile population, or to monitor the travel time between specific points within a watershed ***(Table 9.5)****. However, consideration needs to be given to factors that may influence the success of the population outside the study area. Commercial fishing, disease, predation, limited food supply, or carrying capacity of juvenile or adult habitat may be more important controlling factors than access to spawning and nursery habitat.*

The performance evaluation must allow ample time for the species to complete its life cycle. Many anadromous species have life spans of 4 to 7 years; sturgeon live for decades. Adequate homing to natal areas may require several generations to build a significant migrating population and to fill all year classes. Floods or droughts can impact fry and juvenile life stages and do not become apparent in adult spawning populations until several years have elapsed. Restoration and monitoring goals need to be formulated to take these non-restoration- limiting factors into account. Examination of year-class structure of returning adults might be useful, or investigations that average the size of spawning runs for multiple years might be appropriate.

Table 9.5: Methods to evaluate effectiveness of fish barrier modifications.

Modification	Method
Fishway counts	Observation windows
	Hydroacoustics
	Fish traps/weirs
	Netting
Population estimates	Mark and recapture
	Snorkel counts
	Redd counts
	Creel census
	Direct counts of spawning adults
Timing of migration between observation points	Radio tagging
	Pit tags
	Dyes and other external marks
	Computer-coded tags

Performance evaluation study methodologies must use appropriate monitoring techniques. Collecting techniques need to be relatively nondestructive. Collecting weirs, traps, or nets need to be designed to limit injury or predation and should function over a wide range of flow and debris levels. Monitoring techniques should not extensively limit movement. Weirs and traps should not cause excessive delays in migration, and fish tags should not encumber movement. Techniques are often species- and life stage-specific. Fish tags, including radio tags, may be appropriate for older, larger individuals, whereas chemical marks, dyes, fin clips, or internal microtags may be appropriate for smaller organisms. Certain fish, such as alosids (American shad and river herring), may be more difficult to handle than others, such as salmonids (trout and salmon), and appropriate handling techniques need to be used. Avoiding extreme environmental conditions (excessively high or low water temperature or flow) may be important. Nondestructive techniques, such as hydroacousitics and radio tags, have several advantages, but care needs to be taken to differentiate between background noise (mechanical, debris, entrained air, nonlaminar flow), other species, and target species.

- Consumptive recreation (fishing, hunting)
- Research and educational uses
- Protection of property (erosion control, floodwater retention)

Use surveys, which determine the success of the restoration in terms of human use, can provide additional biological data. Angler survey, creel census, birding questionnaires, and sign-in trail boxes that request observations of specific species can also provide biological data. Citizens' groups can participate effectively, providing valuable assistance at minimal cost.

Figure 9.25: Human interest in the stream corridor. *Aesthetics are a highly valued benefit associated with a healthy stream corridor.*

9.C Restoration Management

Management is the long-term manipulation and protection of restoration resources to achieve objectives. Management priorities for the stream corridor ecosystem are set during the planning phase and refined during design. These priorities should also be subject to ongoing revision based on regular monitoring and analysis. Management needs can range from relatively passive approaches that involve removal of acute impacts to intensive efforts designed to restore ecosystem functions through active intervention. Whereas a preceding section described the need to provide adequate maintenance for the restoration elements, restoration management is the collective set of decisions made to guide the entire restoration effort to success.

The restoration setting and the priorities of participants can make management a fairly straightforward process or a complex process that involves numerous agencies, landowners, and interested citizens. Development of a management plan is less difficult when the corridor and watershed are under the control of a single owner or agency that can clearly state objectives and priorities. Some stream corridor

Additional References for Monitoring

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Management needs can range from relatively passive approaches that involve removal of acute impacts to intensive efforts designed to restore ecosystem functions through active intervention.

restorations have, in fact, involved extensive land acquisition to achieve sufficient management control to make restoration feasible. Even then, competing interests can exist. Decisions must be made regarding which resource uses are compatible with the defined objectives.

More commonly, stream corridor management decisions will be made in an environment of conflicting interests, overlapping mandates and regulatory jurisdictions, and complex ownership patterns, both in the corridor and in the surrounding watershed. For example, in a Charles River corridor project in Massachusetts, the complex ownership pattern along the river requires direct active management in some areas and easements in others. In the remainder, management is largely a matter of encouraging appropriate use (Barron 1989). Many smaller restorations might be similarly diversified with management decisions involving a variety of participants. Participation and adherence to restoration best management practices (BMPs) may be encouraged through various programs, such as the NRCS's Conservation Reserve Program, multi-agency riparian buffer restoration initiatives, and cost-sharing opportunities available under the EPA Section 319 Program.

Programs intended to reduce nonpoint source pollution of waterways often encourage the use of practices to address problems such as agricultural runoff or sediment generated by timber harvest operations. Because many practices focus on activities within the stream corridor, existing practices should be reviewed to determine their applicability to the stream corridor restoration plan (**Figure 9.26**). Although the ecological restoration objectives for the corridor might require more restrictive management, existing practices can provide a good starting point and establish a rationale for minimum management prescriptions. In stream corridor restoration efforts involving numerous landowners, it might be appropriate to develop a revised set of practices specific to the restoration area. Participants should have the opportunity to participate in developing the practices and should be willing to commit to compliance before the restoration is implemented.

Regulatory controls influencing management options are increasingly complex and require regular review as management plans evolve and adapt. In some areas, regulatory oversight of activities in streamside areas and in the vicinity of wetlands involves fairly rigid rules that may conflict with specific proposed management actions (e.g., selective tree removals). Implementation of management actions in such cases will require coordination and approval from the regulating agencies. Many state and local jurisdictions vary their restrictions according to classification systems reflecting the condition of the streamside area or wetland in terms of "naturalness"; for example, sites with large trees might receive a higher level of protection than sites that have been heavily disturbed.

Restoration is intended specifically to improve the condition of the stream corridor; however, an activity that is allowable initially might be regulated as the corridor condition improves. These changes should be anticipated to the extent possible in developing long-term management and use plans.

Streams

In effect, stream corridor restoration and ongoing monitoring constitute stream management. Many problems detected during monitoring can be resolved by manipulation of the stream corridor vegetation (**Figure 9.27**), land uses, where possible, and only occasionally, by direct physical manipulation of the channel. If "resetting" of the channel system is necessary, it essentially becomes a redesign problem.

Where lateral erosion occurs in unanticipated areas and poses an unacceptable threat to function, property, or infrastructure, another restoration approach might have to be initiated.

In cases where streamflow control is an option, it likely will be a significant component of the management plan to maintain baseflows, water temperatures, and other attributes. However, appropriate flow patterns should have been defined during the design phase, with components of corridor management prescribed accordingly. If hydrologic patterns change after the restoration is established, significant redesign or management changes might be required for the entire corridor. Ultimately, a well-planned, prepared stream corridor restoration design predicts and addresses the potential for hydrologic change.

Figure 9.26: Livestock fences used as a BMP. *Reviewing existing BMPs can be useful in establishing management prescriptions.*

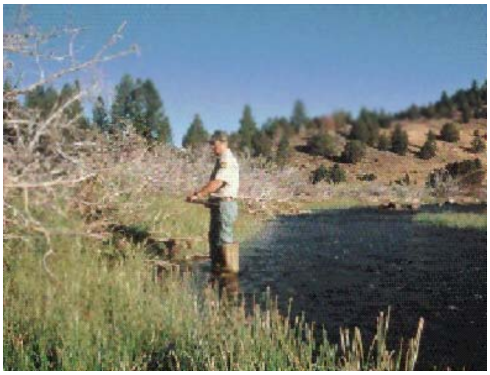

Figure 9.27: Pruning streamside vegetation. *Monitoring might detect the need for manipulation of streamside vegetation.*

Forests

In forested environments, the planning and design phases of stream corridor restoration should set specific objectives for forest structure and composition within the corridor. If existing forests are developing in the desired direction, action may not be needed. In this case, forest management consists of protection rather than intervention. In degraded stream corridor forests, achieving desired goals requires active forest management. In many corridors economic return to private and public landowners is an important objective of the restoration plan. Stream corridor restoration may accommodate economic returns from forest management, but management within the stream corridor should be driven primarily by ecological objectives. If the basic goal is to restore and maintain ecological functions, silviculture should imitate natural processes that normally occur in the corridor.

Numerous forest management activities can promote ecological objectives. For example, some corridor forest types might benefit from prescribed fire or wildfire management programs that maintain natural patterns of structural and compositional diversity and regeneration. In other systems, fire might be inappropriate or might be precluded if the stream corridor is in an urban setting. In the latter case, silvicultural treatments might be needed to emulate the effects of fire.

Recovery of degraded streamside forests can be encouraged and accelerated through silvicultural efforts. Active intervention and management may be essential to maintain the character of native plant communities where river regulation has contributed to hydrology and sedimentation patterns that result in isolation from seed sources (Klimas 1991, Johnson 1994). Streamside forests used as buffers to prevent nutrients from reaching streams may require periodic harvests to remove biomass and maintain net uptake (Lowrance et al. 1984, Welsch 1991). However, buffers intended to intercept and degrade herbicides might be most effective if they are managed to achieve old-growth conditions (Entry et al. 1995).

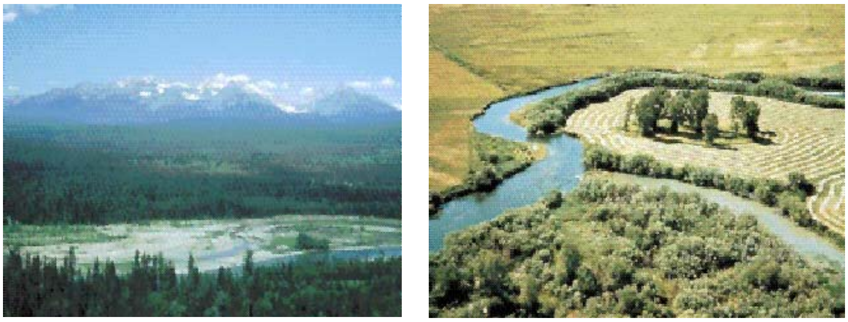

Figure 9.28: Streamside forests and adjacent uplands. *Management of streamside forests should not proceed in isolation from management of adjacent upland systems.*

Management of corridor forests should not proceed in isolation from management of adjacent upland systems (**Figure 9.28**). Upland harvests can result in raised water tables and tree mortality in riparian zones. Coordinated silvicultural activities can reduce timber losses as well as minimize the need for roads (Oliver and Hinckley 1987).

Forests managed by government agencies are usually subject to established restrictions on activities in riparian areas. Elsewhere, BMPs for forestry practices are designed to minimize non-point source pollution and protect water quality. BMPs typically include restrictions on road placement, equipment use, timber removal practices, and other similar considerations. Existing state BMP guidelines may be appropriate for application within the restoration area but often require some modification to reflect the objectives of the restoration or other pre-identified constraints on activities in the vicinity of streams and wetlands.

Grazed Lands

Livestock grazing is a very important stream corridor management issue in most nonforested rangelands and in many forested areas. Uncontrolled livestock grazing can have severe detrimental effects on streambanks, riparian vegetation, and water quality, particularly in arid and semiarid environments (Behnke and Raleigh 1978, Elmore and Beschta 1987, Chaney et al. 1990) (**Figure 9.29**). Livestock naturally concentrate in the vicinity of streams; therefore, special efforts must be made to control or prevent access if stream corridor restoration is to be achieved.

In some cases, livestock may act

Figure 9.29: Livestock in stream. *Uncontrolled livestock grazing can have severe detrimental effects on streambanks, riparian vegetation, and water quality.*

as an agent in restoration. Management of livestock access is critical to ensure their role is a positive one. Existing state BMPs might be sufficient to promote proper grazing, but might not be innovative or adaptive enough to meet the restoration objectives of a corridor management program.

Complete exclusion of livestock is an effective approach to restore and maintain riparian zones that have been badly degraded by grazing. In some cases, exclusion may be sufficient to reverse the damage without additional intervention. In some degraded systems, removal of livestock for a period of years followed by a planned management program may allow recovery without permanent livestock exclusion (Elmore and Beschta 1987). Systems not badly damaged might respond to grazing management involving seasonal and herd size restrictions, off-channel or restricted-access watering, use of riparian pastures, herding, and similar techniques (Chaney et al. 1990). Response to grazing is specific to channel types and season.

In off-channel areas of the stream corridor, grazing may require less intensive management. Grazing might have limited potential to be used as a habitat manipulation tool in certain ecosystems, such as the Northern Plains, where native grazing animals formerly controlled ecosystem structure (Severson 1990). However, where grazing occurs within the stream corridor, it might conflict directly with ecosystem restoration objectives if not properly managed. Corridors that include grazing or have livestock in adjacent areas require vigilance to ensure that fences are maintained and herd management BMPs are followed.

Fish and Wildlife

Stream and vegetation care are the focus of many fish and wildlife management activities in the stream corridor. Hunting and fishing activities (**Figure 9.31**), nuisance animal control, and protection of particular species may be addressed in some restoration plans. Special management units, such as seasonally flooded impoundments specifically designed to benefit particular groups of species (Fredrickson and Taylor 1982), might be appropriate components of the stream corridor, requiring special maintenance and management. Numerous fish and wildlife management tools and techniques that address temporary deficiencies in habitat availability are available (e.g., Martin 1986). Inappropriate or haphazard use of some techniques can have unintended detrimental effects (for example, placing wood duck nest boxes in areas that lack brood habitat). Programs intended to manipulate fish and wildlife populations or habitats should be undertaken in consultation with the responsible state or federal resource agencies.

Restoration of a functional stream corridor can be expected to attract beaver in many areas. Where beaver control is warranted because of possible damage to private timberlands or roads, increased mosquito problems, and other concerns, controls should be placed as soon as possible and not after the damage is done. Techniques are available to prevent beaver from blocking culverts or drain pipes and destroying trees. In some cases, effective beaver control requires removal of problem animals (Olson and Hubert 1994).

Corridors that include grazing or have livestock in adjacent areas require vigilance to ensure that fences are maintained and herd management BMPs are followed.

CASE STUDY

Partners Working for the Big Spring Creek Watershed

The Big Spring Creek watershed occupies a diverse, primarily agricultural landscape in central Montana, where the nation's third largest freshwater spring (Big Springs) provides untreated drinking water for the 7,000 residents of Lewistown and is the source of one of Montana's best trout streams, Big Spring Creek.

Conservation work by federal, state, and local agencies, private organizations, and citizens in the 255,000-acre Big Spring Creek watershed is not new. Actually, various projects and developments have occurred over the last several decades. For example, the flood control project that protects the city of Lewistown has its roots in the 1960s when, after experiencing a series of floods, the city of Lewistown and community leaders decided to take action. The Fergus County Conservation District, Fergus County Commissioners, City of Lewistown, U.S. Natural Resources Conservation Service, and many community leaders all worked together on this project. The Big Spring Creek Flood Control Project now protects the city of Lewistown from recurrent flooding.

Conservation work now, though, goes beyond flood control. It involves working to solve resource problems on a watershed basis, recognizing that what happens upstream has an effect on the downstream resources. We should look beyond property boundaries at the whole watershed, considering the "cumulative effects" of all our actions. With that in mind, the Fergus County Conservation District, with assistance from its citizen committee, has been working the last few years to improve and protect the watershed. With funding from the Montana Department of Environmental Quality (Section 319), the Big Spring Creek Watershed Partnership was formed.

This project helps agricultural producers and other landowners to plan and install conservation practices to prevent erosion and keep sediment and other pollutants out of streams and lakes. Area landowners are implementing *conservation practices such as improving the riparian vegetation* ***(Figure 9.30)****, treating streambank erosion, and developing water sources off the stream for livestock. Because the project has been well received by the agricultural producers, it has been possible for cooperating agencies to participate in additional watershed improvements. The U.S. Fish and Wildlife Service Partners for Wildlife program has provided funding for several stream restoration and riparian improvement projects. In addition, the Montana Department of Fish, Wildlife and Parks is actively participating in fisheries habitat projects, including the Brewery Flats Stream Restoration.*

Implementation of the Big Spring Creek Watershed Partnership has brought many positive changes to the predominantly agricultural Big Spring Creek watershed. Since most of the agricultural operations are livestock or grain, the major emphasis is on riparian/stream improvement and grazing management. Thus far, more than 30 landowners have participated in the project by installing conservation practices that include over 8 miles of fencing, and 13 off-stream water developments, with more than 10 miles of stream/riparian area protected.

Studies show that stream characteristics and water quality are the best indicators of watershed vitality. Thus, an active monitoring strategy in the watershed provides feedback to measure any improvements. Preproject and postproject fisheries (trout) surveys are conducted in cooperation with the Montana Department of Fish, Wildlife and Parks on selected streams. On East Fork Spring Creek, fencing and off-stream water development were implemented on a riparian/stream reach that was severely degraded from livestock use. Fish populations and size structure changed dramatically from preproject to postproject work. Salmonid numbers increased from 12 to 32 per 1,000 feet, and average size increased by 50 percent. In addition to fisheries surveys, benthic macroinvertebrate communities are collected and analyzed on a number of streams. This analysis relates to the stream's biological health or integrity. Community structure, function, and sensitivity to impact are compared to baseline data. Habitat conditions on three of six monitoring sites on Big Spring Creek from 1990 to 1997 have shown improved conditions from a sub-optimal to an optimal rating. Monitoring will continue on major streams in the watershed, which will help to provide important feedback as to the project's effectiveness.

Although the major emphasis is on improving and protecting the riparian areas and streams in the watershed, other ongoing efforts include participating in the "Managing Community Growth" initiative, preserving agriculture and open space, and developing recreational and environmental resources. An active committee of the group is involved in one of the largest stream restoration initiatives ever to be undertaken in Montana, planned for 1998. Included in this project is an environmental education trail site being developed with the local schools.

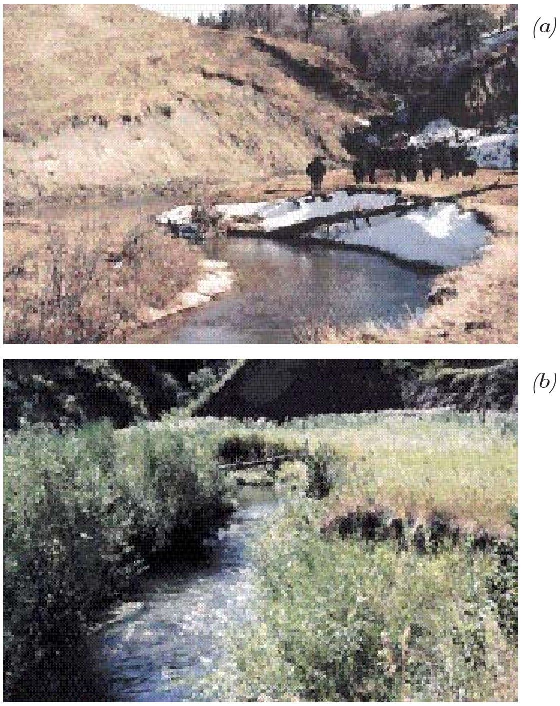

Figure 9.30: The Big Spring Creek watershed. *(a) A heavily impacted tributary within the Big Spring Creek watershed and (b) the same tributary after restoration.*

Working with watersheds is a dynamic process, and as a result new activities and partners are continually incorporated into the Big Spring Creek Watershed Partnership. The following agencies and organizations are currently working together with the citizens of the watershed to protect this "very special place."

Fergus County Conservation District

M.S.U.-Extension Service, Fergus County

U.S. Natural Resources Conservation Service

U.S. Fish and Wildlife Service

Montana Department of Fish, Wildlife and Parks

Montana Department of Environmental Quality

Montana Department of Natural Resources and Conservation

U.S. Forest Service

City Of Lewistown

Fergus County Commissioners

Snowy Mountain Chapter Trout Unlimited

Central Montana Pheasants Forever

Lewistown School District No.1

Lewistown Visioning Group

Lewistown Area Chamber of Commerce

Human Use

Stream corridors in urban areas are usually used heavily by people and require much attention to minimize, control, or repair human impacts. In some cases, human disturbance prevents some stream corridor functions from being restored. For example, depending on the amount of degradation that has occurred, urban streams might support relatively few, if any, native wildlife species. Other concerns, such as improved water quality, might be addressed effectively through proper restoration efforts. Addressing impacts from surrounding developed areas (such as uncontrolled storm water runoff and predation by pets) requires coordination with community agencies and citizen groups to minimize, prevent, or reverse damage. Management of urban corridors might tend to emphasize recreation, educational opportunities, and community activities more than ecosystem functions. Administrative concerns may focus heavily on local ordinances, zoning, and construction permit standards and limitations.

Figure 9.31: Local fisherman. *Fishing and other recreational activities must be considered in restoration management.*

Community involvement can be an important aspect of urban stream corridor restoration and management. Community groups often initiate restoration and maintain a feeling of ownership that translates into monitoring input, management oversight, and volunteer labor to conduct maintenance and management activities. It is essential that community groups be provided with professional technical gui-

CASE STUDY

A Creek Ran Through It

Portland, Oregon, sprang up along the Willamette River. As time went on and the city grew, it came to occupy a sequestered spot between the Willamette and Columbia Rivers and the higher reaches of the Sylvan Hills. But before the city expanded to this point, a creek ran through it—Tanner Creek.

The Tanner Creek watershed, comprising approximately 1,600 acres, extended from the forested hills through a canyon and across the valley floor to the Willamette River. During summer months, the creek was placid if not dry. But during the heavy winter rains, the creek became a raging torrent.

As the city of Portland expanded, the creek was diverted into the sewer system and the creek floodway was filled in to make way for development. These combined sewers drained directly to the Willamette River and the Columbia Slough until a series of interceptor pipes and a municipal sewage treatment plant were constructed in the 1940s and 1950s.

However, this new system did not have sufficient capacity to handle the combined sewage and storm water flows during periods of heavy rain, which frequently occur during the winter months. As a result, rather than flowing to the treatment plant for processing and disinfection, the combined sewage and storm water overflowed to outfalls along the Willamette River and the Columbia Slough. Tanner Creek became a part of the cause of combined sewer overflows (CSOs).

In the early 1990s, the city of Portland began to develop a plan to eliminate CSOs. The Tanner Creek Stream Diversion Project was identified early in the CSO planning process as a corner-stone project, a relatively inexpensive method of removing clean storm water from the combined system, thereby reducing CSOs. Nearly 10 miles of pipe ranging from 84 inches to 60 inches in diameter will be constructed to once again carry storm water directly to the river. In addition, best management practices for storm water management will be included. Finally, opportunities for water feature enhancements and educational and cultural opportunities will be explored in partnership with the community and other agencies.

Principal among these opportunities is daylighting a portion of the stream in the city's River District. In partnership with community leaders, special interest groups, a private developer, and other agencies, the city's Bureau of Environmental Services is leading a study of possible design alternatives. For more information contact: Nea Lynn Robinson, Project Manager, Tanner Creek Stream Diversion Project, City of Portland, Oregon.

dance including assistance in translating regulatory requirements. It is also important that proposed management actions in urban corridors be discussed in advance with interested groups affected by tree cutting or trail closures.

In nonurban areas, recreation can usually be accommodated without impairing ecological functions if all concerned parties consider ecosystem integrity to be the priority objective (Johnson and Carothers 1982). Strategies can be devised and techniques are available to minimize impacts from activities such as camping, hiking (trail erosion), and even the use of off-road vehicles (Cole and Marion 1988) (**Figure 9.32**). Recreationists should be educated on methods to minimize impacts on the ecosystem and on restoration structures and vegetation. Location of areas designated for low-impact use and areas off-limits to certain high-impact activities (such as off-road vehicles, biking, horse-back riding, etc.) should be clearly marked. Access should be restricted to areas where new vegetation has not yet been fully established or where vegetation could be damaged beyond the point of survival.

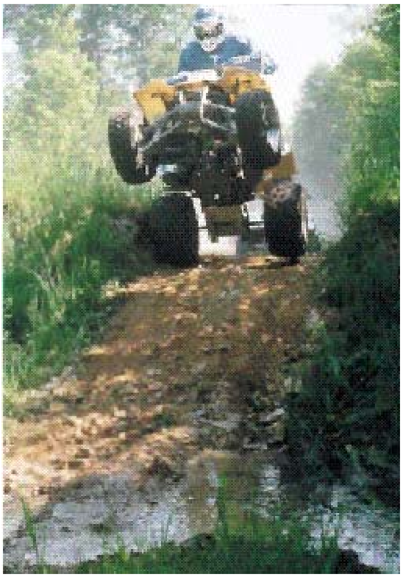

Figure 9.32: Off-road vehicle. *Low- and high-impact use areas hould be clearly marked within public tream corridors.*

All the flowers of all the tomorrows are in the seeds of today.
—Chinese proverb

There will come a time when you believe everything is finished. That will be the beginning.
—Louis L'Amour

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- Bureau of Land Management
- Bureau of Reclamation
- Fish and Wildlife Service
- National Park Service
- U.S. Geological Survey

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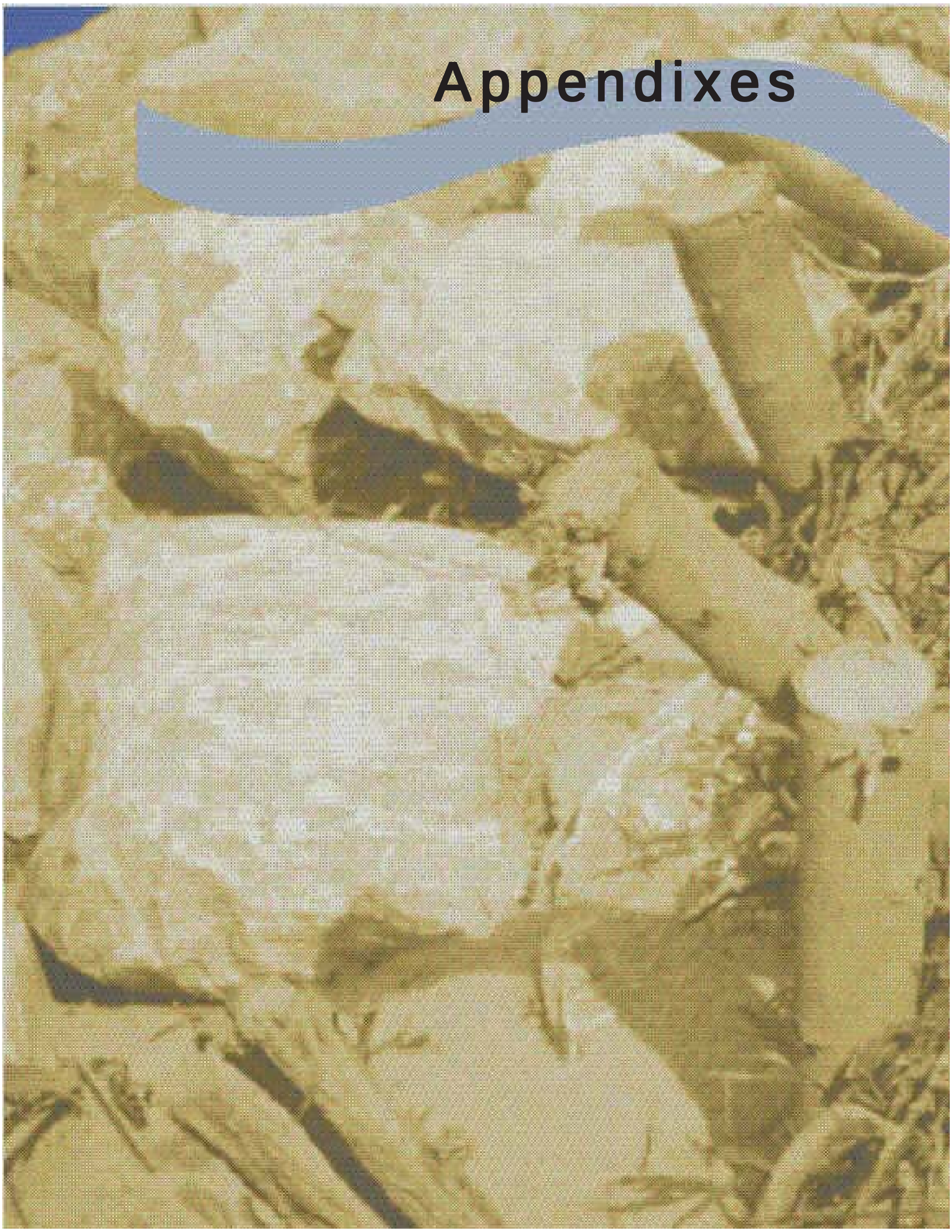
Appendixes



APPENDIX A

> *"The outstanding scientific discovery of the twentieth century is not television, or radio, but rather the complexity of the land organism. Only those who know the most about it can appreciate how little we know about it. The last word in ignorance is the man who says of an animal or plant: "What good is it?" If the land mechanism as a whole is good, then every part is good, whether we understand it nor not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering."*
>
> Aldo Leopold 1953, pp. 145-146

The user of this document is cautioned not to attempt to replicate or apply any of the techniques displayed without determining their appropriateness as an integral part of the restoration plan.

Introduction

The following are presented as examples of the many techniques that are being used in support of stream corridor restoration. Only a limited number of techniques by broad category are shown as examples. Neither the number of examples nor their descriptions are intended to be exhaustive. The examples are conceptual and contain little design guidance. All restoration techniques, however, should be designed; often through an interdisciplinary approach discussed in Part II of this document. Limited guidance is provided on applications, but local standards, criteria, and specifications should always be used.

These and other techniques have specific ranges of applicability in terms of physical and climate adaptation, as well as for different physiographic regions of the country. Techniques that are selected must be components of a system designed to restore specific functions and values to the stream corridor.

The use of any single technique, without consideration of system functions and values, may become a short-lived, ineffective fix laid on a system-wide problem. All restoration techniques are most effective when included as an integral part of a restoration plan. Typically a combination of techniques are prescribed to address prevailing conditions and desired goals.

Effective restoration will respond to goals and objectives that are determined locally through the planning process described in Chapters 4 though 6.

The restoration plan may prescribe a variety of approaches depending on the condition of the stream corridor and the restoration goals:

- *No action.* Simply remove disturbance factors and "let nature heal itself."
- *Managemen*t. Modify disturbance factors to allow continued use of the corridor, while the system recovers.
- *Manipulatio*n. Change watershed, corridor, or stream conditions through land use changes, intervention, and designed systems ranging from installing practices to altering flow conditions, to changing stream morphology and alignment.

Regardless of the techniques applied, they should restore the desired functions and achieve the goals of the restoration plan. The following are general considerations that apply to many or all of the techniques in this appendix:

- The potential adverse impacts from failure of these and other techniques should be assessed before they are used.
- Techniques that change the channel slope or cross section have a high potential for causing channel instability upstream and downstream. They should therefore be analyzed and designed by an interdisciplinary team of professionals. These techniques include: weirs, sills, grade control measures, channel realignment, and meander reconstruction.
- The potential impact on flood elevations should be analyzed before these and other techniques are used.
- Many techniques will not endure on streams subject to headcuts or general bed degradation.
- Some form of toe protection will be required for many bank treatment techniques to endure where scour of the streambank toe is anticipated.
- Any restoration technique installed in or in contact with streams, wetlands, floodplains, or other water bodies are subject to various federal, state, and local regulatory programs and requirements. Most techniques presented in this appendix would require the issuance of permits by federal, state, and local agencies prior to installation.

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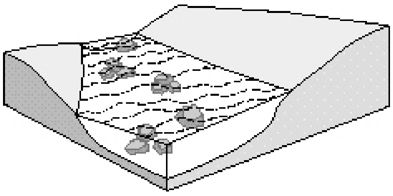
INSTREAM PRACTICES

Boulder Clusters



Groups of boulders placed in the base flow channel to provide cover, create scour holes, or areas of reduced velocity.

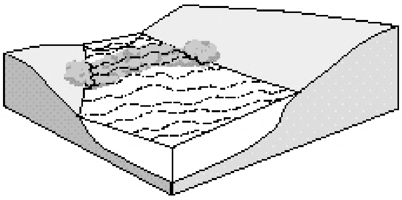
Applications and Effectiveness

- Can be used in most stream habitat types including riffles, runs, flats, glides and open pools.
- Greatest benefits are realized in streams with average flows exceeding 2 feet per second.
- Group placements are most desirable. Individual boulder placement might be effective in very small streams.
- Most effective in wide, shallow streams with gravel or rubble beds.
- Also useful in deeper streams for providing cover and improving substrate.
- Not recommended for sand bed (and smaller bed materials) streams because they tend to get buried.
- Added erosive forces might cause channel and bank failures.
- Not recommended for streams which are aggrading or degrading.
- May promote bar formation in streams with high bed material load.

For More Information

- Consult the following references: Nos. 11, 13, 21, 34, 39, 55, 60, 65, 69.

Weirs or Sills



Log, boulder, or quarrystone structures placed across the channel and anchored to the streambank and/or bed to create pool habitat, control bed erosion, or collect and retain gravel.

Applications and Effectiveness

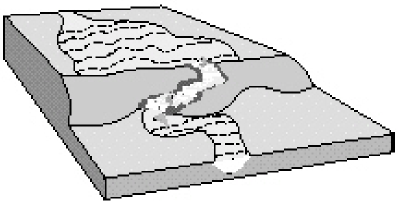
- Create structural and hydraulic diversity in uniform channels.
- If placed in series, they should not be so close together that all riffle and run habitat is eliminated.
- Pools will rapidly fill with sediment in streams transporting heavy bed material loads.
- Riffles often are created in downstream deposition areas.
- Weirs placed in sand bed streams are subject to failure by undermining.
- Potential to become low flow migration barriers.
- Selection of material is important.
  - Boulder weirs are generally more permeable than other materials and might not perform well for funneling low flows. Voids between boulders may be chinked with smaller rock and cobbles to maintain flow over the crest.
  - Large, angular boulders are most desirable to prevent movement during high flows.
  - Log weirs will eventually decompose.
- Design cross channel shape to meet specific need(s).
  - Weirs placed perpendicular to flow work well for creating backwater.
  - Diagonal orientations tend to redistribute scour and deposition patterns immediately downstream.
  - Downstream “V’s” and “U’s” can serve specific functions but caution should be exercised to prevent failures.
  - Upstream “V’s” or “U’s” provide mid-channel, scour pools below the weir for fish habitat, resting, and acceleration maneuvers during fish passage.
  - Center at lower elevation than sides will maintain a concentrated low flow channel.

For More Information

- Consult the following references: Nos. 11, 13, 44, 55, 58, 60, 69.

INSTREAM PRACTICES

Fish Passages



Any one of a number of instream changes which enhance the opportunity for target fish species to freely move to upstream areas for spawning, habitat utilization, and other life functions.

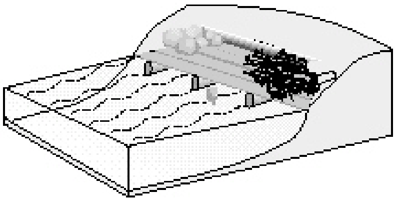
Applications and Effectiveness

- Can be appropriate in streams where natural or human placed obstructions such as waterfalls, chutes, logs, debris accumulations, beaver dams, dams, sills, and culverts interfere with fish migration.
- The aquatic ecosystem must be carefully evaluated to assure that fish passages do not adversely impact other aquatic biota and stream corridor functions.
- Slopes, depths and relative positions of the flow profile for various flow ranges are important considerations. Salmonids, for example, can easily negotiate through vertical water drops where the approach pool depth is 1.25 times the height of the (drop subject to an overall species-specific limit on height) (CA Dept. of Fish and Game, 1994).
- The consequences of obstruction removal for fish passage must be carefully evaluated. In some streams, obstructions act as barriers to undesirable exotics (e.g. sea lamprey) and are useful for scouring and sorting of materials, create important backwater habitat, enhance organic material input, serve as refuge for assorted species, help regulate water temperature, oxygenate water, and provide cultural resources.
- Designs vary from simple to complex depending on the site and the target species.

For More Information

- Consult the following references: Nos., 11, 69, 81.

Log/Brush/Rock Shelters



Logs, brush, and rock structures installed in the lower portion of streambanks to enhance fish habitat, encourage food web dynamics, prevent streambank erosion, and provide shading.

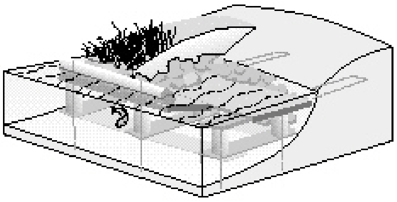
Applications and Effectiveness

- Most effective in low gradient stream bends and meanders where open pools are already present and overhead cover is needed.
- Create an environment for insects and other organisms to provide an additional food source.
- Can be constructed from readily available materials found near the site.
- Not appropriate for unstable streams which are experiencing severe bank erosion and/or bed degradation unless integrated with other stabilization measures.
- Important in streams where aquatic habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Not generally as effective on the inside of bendways.

For More Information

- Consult the following references: Nos. 11, 13, 39, 55, 65.

Lunker Structures



Cells constructed of heavy wooden planks and blocks which are imbedded into the toe of streambanks at channel bed level to provide covered compartments for fish shelter, habitat, and prevention of streambank erosion.

Applications and Effectiveness

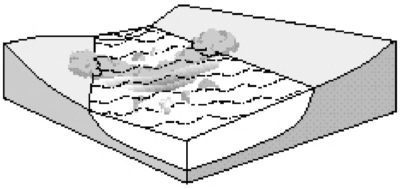
- Appropriate along outside bends of streams where water depths can be maintained at or above the top of the structure.
- Suited to streams where fish habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Are often used in conjunction with wing deflectors and weirs to direct and manipulate flows.
- Are not recommended for streams with heavy bed material loads.
- Most commonly used in streams with gravel-cobble beds.
- Heavy equipment may be necessary for excavating and installing the materials.
- Can be expensive.

For More Information

- Consult the following references: Nos. 10, 60, 65, 85.

INSTREAM PRACTICES

Migration Barriers



Obstacles placed at strategic locations along streams to prevent undesirable species from accessing upstream areas.

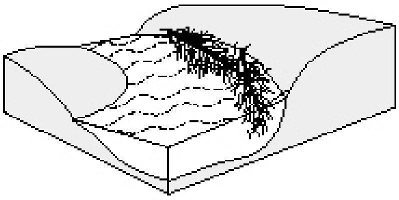
Applications and Effectiveness

- Effective for specific fishery management needs such as separating species or controlling nuisance species by creating a barrier to migration.
- Must be carefully evaluated to assure migration barriers do not adversely impact other aquatic biota and stream corridor functions.
- Both physical structures or electronic measures can be used as barriers.
  - Structures can be installed across most streams, but in general they are most practical in streams with baseflows depths under two feet and widths under thirty feet.
  - Temporary measures such as seines can also be used under the above conditions.
  - Electronic barriers can be installed in deeper channels to discourage passage. Electronic barrier employs lights, electrical pulses or sound frequencies to discourage fish from entering the area. This technique has the advantage of not disturbing the stream and providing a solution for control in deep water.
- Barriers should be designed so that flood flows will not flank them and cause failures.

For More Information

- Consult the following references: Nos. 11, 55.

Tree Cover



Felled trees placed along the streambank to provide overhead cover, aquatic organism substrate and habitat, stream current deflection, scouring, deposition, and drift catchment.

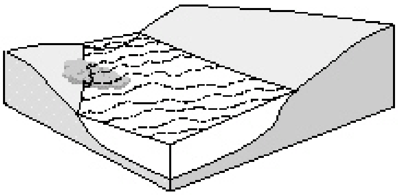
Applications and Effectiveness

- Can provide benefits at a low installation cost.
- Particularly advantageous in streams where the bed is unstable and felled trees can be secured from the top of bank.
- Channels must be large enough to accommodate trees without threatening bank erosion and limiting needed channel flow capacity.
- Design of adequate anchoring systems is necessary.
- Not recommended if debris jams on downstream bridges might cause subsequent problems.
- Require frequent maintenance.
- Susceptible to ice damage.

For More Information

- Consult the following references: Nos. 11, 55, 69.

Wing Deflectors



Structures that protrude from either streambank but do not extend entirely across a channel. They deflect flows away from the bank, and scour pools by constricting the channel and accelerating flow.

Applications and Effectiveness

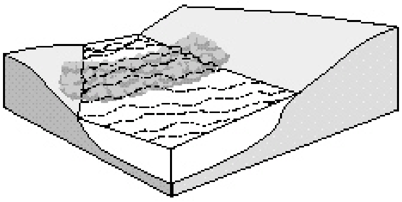
- Should be designed and located far enough downstream from riffle areas to avoid backwater effects that would drown out or otherwise damage the riffle.
- Should be sized based on anticipated scour.
- The material washed out of scour holes is usually deposited a short distance downstream to form a bar or riffle area. These areas of deposition are often composed of clean gravels that provide excellent habitat for certain species.
- Can be installed in series on alternative streambanks to produce a meandering thalweg and associated structural diversity.
- Rock and rock-filled log crib deflector structures are most common.
- Should be used in channels with low physical habitat diversity, particularly those with a lack of stable pool habitat.
- Deflectors placed in sand bed streams may settle or fail due to erosion of sand, and in these areas a filter layer or geotextile might be needed underneath the deflector.

For More Information

- Consult the following references: Nos. 10, 11, 18, 21, 34, 48, 55, 59, 65, 69, 77.

INSTREAM PRACTICES

Grade Control Measures



Rock, wood, earth, and other material structures placed across the channel and anchored in the streambanks to provide a “hard point” in the streambed that resists the erosion forces of the degradational zone, and/or to reduce the upstream energy slope to prevent bed scour.

Applications and Effectiveness

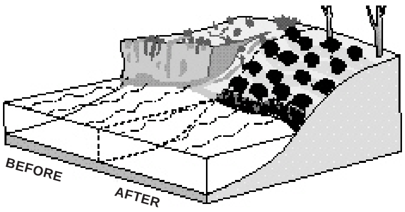
- If a stable channel bed is essential to the design, grade control should be considered as a first step before any restoration measures are implemented (if degradational processes exist in channel system).
- Used to stop headcutting in degrading channels.
- Used to build bed of incised stream to higher elevation.
- Can improve bank stability in an incised channel by reducing bank heights.
- Man-made scour holes downstream of structures can provide improved aquatic habitat.
- Upstream pool areas created by structures provide increased low water depths for aquatic habitat.
- Potential to become low flow migration barrier.
- Can be designed to allow fish passage.
- If significant filling occurs upstream of structure, then downstream channel degradation may result.
- Upstream sediment deposition may cause increased meandering tendencies.
- Siting of structures is critical component of design process, including soil mechanics and geotechnical engineering.
- Design of grade control structures should be accomplished by an experienced river engineer.

For More Information

- Consult the following references: Nos. 1, 4, 5, 6, 7, 12, 17, 18, 25, 26, 31, 37, 40, 63, 66, 84.

STREAMBANK TREATMENT

Bank Shaping and Planting



Regrading streambanks to a stable slope, placing topsoil and other materials needed for sustaining plant growth, and selecting, installing and establishing appropriate plant species.

Applications and Effectiveness

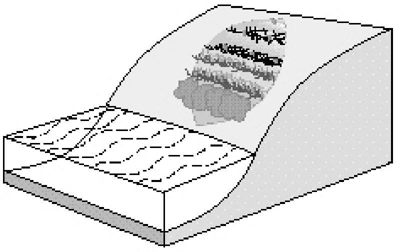
- Most successful on streambanks where moderate erosion and channel migration are anticipated.
- Reinforcement at the toe of the embankment is often needed.
- Enhances conditions for colonization of native species.
- Used in conjunction with other protective practices where flow velocities exceed the tolerance range for available plants, and where erosion occurs below base flows.
- Streambank soil materials, probable groundwater fluctuation, and bank loading conditions are factors for determining appropriate slope conditions.
- Slope stability analyses are recommended.

For More Information

- Consult the following references: Nos. 11, 14, 56, 61, 65, 67, 68, 77, 79.

STREAMBANK TREATMENT

Branch Packing



Alternate layers of live branches and compacted backfill which stabilize and revegetate slumps and holes in streambanks.

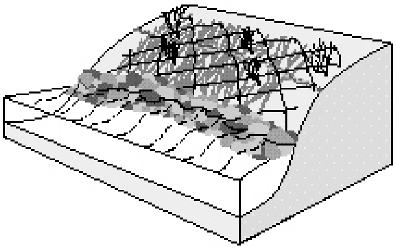
Applications and Effectiveness

- Commonly used where patches of streambank have been scoured out or have slumped leaving a void.
- Appropriate after stresses causing the slump have been removed.
- Less commonly used on eroded slopes where excavation is required to install the branches.
- Produces a filter barrier that prevents erosion and scouring from streambank or overbank flows.
- Rapidly establishes a vegetated streambank.
- Enhances conditions for colonization of native species.
- Provides immediate soil reinforcement.
- Live branches serve as tensile inclusions for reinforcement once installed.
- Typically not effective in slump areas greater than four feet deep or four feet wide.

For More Information

- Consult the following references: Nos. 14, 21, 34, 79, 81.

Brush Mattresses



Combination of live stakes, live facines, and branch cuttings installed to cover and physically protect streambanks; eventually to sprout and establish numerous individual plants.

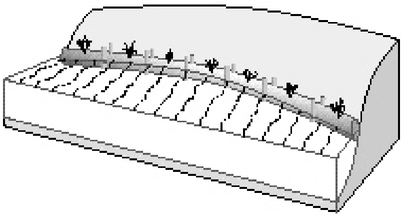
Applications and Effectiveness

- Form an immediate protective cover over the streambank.
- Capture sediment during flood flows.
- Provide opportunities for rooting of the cuttings over the streambank.
- Rapidly restores riparian vegetation and streamside habitat.
- Enhance conditions for colonization of native vegetation.
- Limited to the slope above base flow levels.
- Toe protection is required where toe scour is anticipated.
- Appropriate where exposed streambanks are threatened by high flows prior to vegetation establishment.
- Should not be used on slopes which are experiencing mass movement or other slope instability.

For More Information

- Consult the following references: Nos. 14, 21, 34, 56, 65, 77, 79, 81.

Coconut Fiber Roll



Cylindrical structures composed of coconut husk fibers bound together with twine woven from coconut material to protect slopes from erosion while trapping sediment which encourages plant growth within the fiber roll.

Applications and Effectiveness

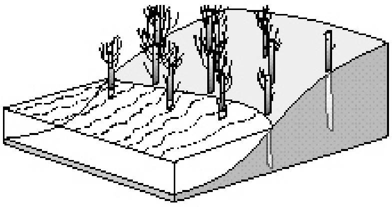
- Most commonly available in 12 inch diameter by 20 foot lengths.
- Typically staked near the toe of the streambank with dormant cuttings and rooted plants inserted into slits cut into the rolls.
- Appropriate where moderate toe stabilization is required in conjunction with restoration of the streambank and the sensitivity of the site allows for only minor disturbance.
- Provide an excellent medium for promoting plant growth at the water's edge.
- Not appropriate for sites with high velocity flows or large ice build up.
- Flexibility for molding to the existing curvature of the streambank.
- Requires little site disturbance.
- The rolls are buoyant and require secure anchoring.
- Can be expensive.
- An effective life of 6 to 10 years.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streamside vegetation.
- Enhances conditions for colonization of native vegetation.

For More Information

- Consult the following references: Nos. 65, 77.

STREAMBANK TREATMENT

Dormant Post Plantings



Plantings of cottonwood, willow, poplar, or other species embedded vertically into streambanks to increase channel roughness, reduce flow velocities near the slope face, and trap sediment.

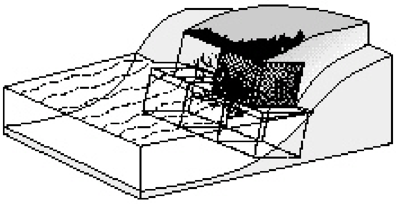
Applications and Effectiveness

- Can be used as live piling to stabilize rotational failures on streambanks where minor bank sloughing is occurring.
- Useful for quickly establishing riparian vegetation, especially in arid regions where water tables are deep.
- Will reduce near bank stream velocities and cause sediment deposition in treated areas.
- Reduce streambank erosion by decreasing the near-bank flow velocities.
- Generally self-repairing and will restem if attacked by beaver or livestock; however, provisions should be made to exclude such herbivores where possible.
- Best suited to non-gravely streams where ice damage is not a problem.
- Will enhance conditions for colonization of native species.
- Are less likely to be removed by erosion than live stakes or smaller cuttings.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streamside vegetation.
- Unlike smaller cuttings, post harvesting can be very destructive to the donor stand, therefore, they should be gathered as ‘salvage’ from sites designated for clearing, or thinned from dense stands.

For More Information

- Consult the following references: Nos. 65, 77, 79.

Vegetated Gabions



Wire-mesh, rectangular baskets filled with small to medium size rock and soil and laced together to form a structural toe or sidewall. Live branch cuttings are placed on each consecutive layer between the rock filled baskets to take root, consolidate the structure, and bind it to the slope.

Applications and Effectiveness

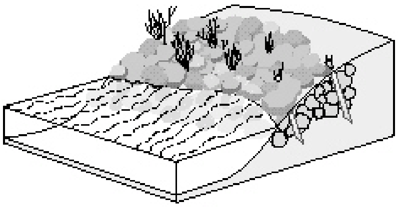
- Useful for protecting steep slopes where scouring or undercutting is occurring or there are heavy loading conditions.
- Can be a cost effective solution where some form of structural solution is needed and other materials are not readily available or must be brought in from distant sources.
- Useful when design requires rock size greater than what is locally available.
- Effective where bank slope is steep and requires moderate structural support.
- Appropriate at the base of a slope where a low toe wall is needed to stabilize the slope and reduce slope steepness.
- Will not resist large, lateral earth stresses.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Require a stable foundation.
- Are expensive to install and replace.
- Appropriate where channel side slopes must be steeper than appropriate for riprap or other material, or where channel toe protection is needed, but rock riprap of the desired size is not readily available.
- Are available in vinyl coated wire as well as galvanized steel to improve durability.
- Not appropriate in heavy bedload streams or those with severe ice action because of serious abrasion damage potential.

For More Information

- Consult the following references: Nos. 11, 18, 34, 56, 77.

STREAMBANK TREATMENT

Joint Plantings



Live stakes tamped into joints or openings between rock which have previously been installed on a slope or while rock is being placed on the slope face.

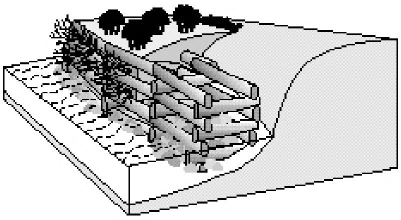
Applications and Effectiveness

- Appropriate where there is a lack of desired vegetative cover on the face of existing or required rock riprap.
- Root systems provide a mat upon which the rock riprap rests and prevents loss of fines from the underlying soil base.
- Root systems also improve drainage in the soil base.
- Will quickly establish riparian vegetation.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Have few limitations and can be installed from base flow levels to top of slope, if live stakes are installed to reach ground water.
- Survival rates can be low due to damage to the cambium or lack of soil/ stake interface.
- Thick rock riprap layers may require special tools for establishing pilot holes.

For More Information

- Consult the following references: Nos. 21, 34, 65, 77, 81.

Live Cribwalls



Hollow, box-like interlocking arrangements of untreated log or timber members filled above baseflow with alternate layers of soil material and live branch cuttings that root and gradually take over the structural functions of the wood members.

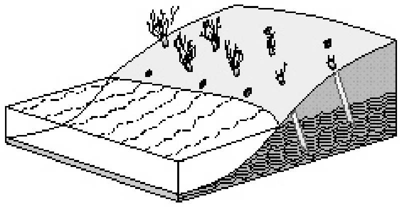
Applications and Effectiveness

- Provide protection to the streambank in areas with near vertical banks where bank sloping options are limited.
- Afford a natural appearance, immediate protection and accelerate the establishment of woody species.
- Effective on outside of bends of streams where high velocities are present.
- Appropriate at the base of a slope where a low wall might be required to stabilize the toe and reduce slope steepness.
- Appropriate above and below water level where stable streambeds exist.
- Don’t adjust to toe scour.
- Can be complex and expensive.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.

For More Information

- Consult the following references: Nos. 11, 14, 21, 34, 56, 65, 77, 81.

Live Stakes



Live, woody cuttings which are tamped into the soil to root, grow and create a living root mat that stabilizes the soil by reinforcing and binding soil particles together, and by extracting excess soil moisture.

Applications and Effectiveness

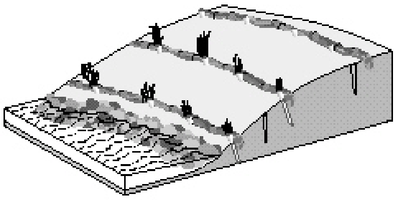
- Effective where site conditions are uncomplicated, construction time is limited, and an inexpensive method is needed.
- Appropriate for repair of small earth slips and slumps that are frequently wet.
- Can be used to stake down surface erosion control materials.
- Stabilize intervening areas between other soil bioengineering techniques.
- Rapidly restores riparian vegetation and streamside habitat.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings.
- Enhance conditions for colonization of vegetation from the surrounding plant community.
- Requires toe protection where toe scour is anticipated.

For More Information

- Consult the following references: Nos. 14, 21, 34, 56, 65, 67, 77, 79, 81.

STREAMBANK TREATMENT

Live Fascines



Dormant branch cuttings bound together into long sausage-like, cylindrical bundles and placed in shallow trenches on slopes to reduce erosion and shallow sliding.

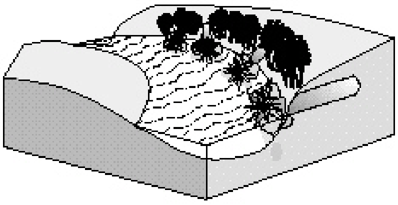
Applications and Effectiveness

- Can trap and hold soil on streambank by creating small dam-like structures and reducing the slope length into a series of shorter slopes.
- Facilitate drainage when installed at an angle on the slope.
- Enhance conditions for colonization of native vegetation.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings.
- Requires toe protection where toe scour is anticipated.
- Effective stabilization technique for streambanks, requiring a minimum amount of site disturbance.
- Not appropriate for treatment of slopes undergoing mass movement.

For More Information

- Consult the following references: Nos. 14, 21, 34, 65, 77, 81.

Log, Rootwad, and Boulder Revetments



Boulders and logs with root masses attached placed in and on streambanks to provide streambank erosion, trap sediment, and improve habitat diversity.

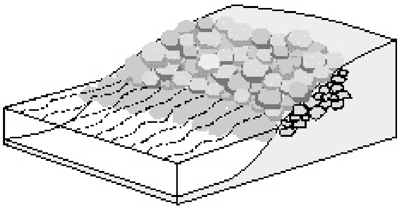
Applications and Effectiveness

- Will tolerate high boundary shear stress if logs and rootwads are well anchored.
- Suited to streams where fish habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Will enhance diversity in riparian areas when used with soil bioengineering systems.
- Will have limited life depending on climate and tree species used. Some species, such as cottonwood or willow, often sprout and accelerate colonization.
- Might need eventual replacement if colonization does not take place or soil bioengineering systems are not used.
- Use of native materials can sequester sediment and woody debris, restore streambanks in high velocity streams, and improve fish rearing and spawning habitat.
- Site must be accessible to heavy equipment.
- Materials might not be readily available at some locations.
- Can create local scour and erosion.
- Can be expensive.

For More Information

- Consult the following references: Nos. 11, 34, 77.

Riprap



A blanket of appropriately sized stones extending from the toe of slope to a height needed for long term durability.

Applications and Effectiveness

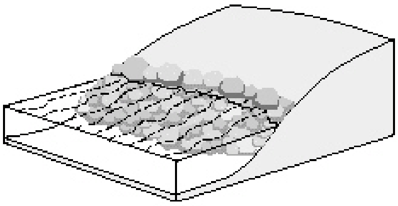
- Can be vegetated (see joint plantings).
- Appropriate where long term durability is needed, design discharge are high, there is a significant threat to life or high value property, or there is no practical way to otherwise incorporate vegetation into the design.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Flexible and not impaired by slight movement from settlement or other adjustments.
- Should not be placed to an elevation above which vegetative or soil bioengineering systems are an appropriate alternative.
- Commonly used form of bank protection.
- Can be expensive if materials are not locally available.

For More Information

- Consult the following references: Nos. 11, 14, 18, 34, 39, 56, 67, 70, 77.

STREAMBANK TREATMENT

Stone Toe Protection



A ridge of quarried rock or stream cobble placed at the toe of the streambank as an armor to deflect flow from the bank, stabilize the slope and promote sediment deposition.

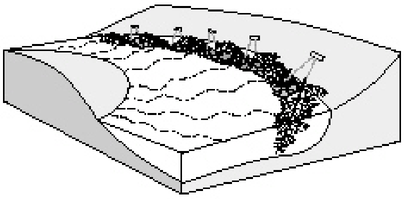
Applications and Effectiveness

- Should be used on streams where banks are being undermined by toe scour, and where vegetation cannot be used.
- Stone prevents removal of the failed streambank material that collects at the toe, allows revegetation and stabilizes the streambank.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerated source of streamside vegetation.
- Can be placed with minimal disturbance to existing slope, habitat, and vegetation.

For More Information

- Consult the following references: Nos. 10, 21, 56, 67, 77, 81.

Tree Revetments



A row of interconnected trees attached to the toe of the streambank or to deadmen in the streambank to reduce flow velocities along eroding streambanks, trap sediment, and provide a substrate for plant establishment and erosion control.

Applications and Effectiveness

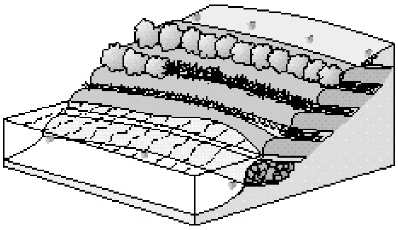
- Design of adequate anchoring systems is necessary.
- Wire anchoring systems can present safety hazards.
- Work best on streams with streambank heights under 12 feet and bankfull velocities under 6 feet per second.
- Use inexpensive, readily available materials.
- Capture sediment and enhances conditions for colonization of native species particularly on streams with high bed material loads.
- Limited life and must be replaced periodically.
- Might be severely damaged by ice flows.
- Not appropriate for installation directly upstream of bridges and other channel constrictions because of the potential for downstream damages should the revetment dislodge.
- Should not be used if they occupy more than 15 percent of the channel's cross sectional area at bankfull level.
- Not recommended if debris jams on downstream bridges might cause subsequent problems.
- Species that are resistant to decay are best because they extend the establishment period for planted or volunteer species that succeed them.
- Requires toe protection where toe scour is anticipated.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerated source of streamside vegetation.

For More Information

- Consult the following references: Nos. 11, 21, 34, 56, 60, 77, 79.

STREAMBANK TREATMENT

Vegetated Geogrids



Alternating layers of live branch cuttings and compacted soil with natural or synthetic geotextile materials wrapped around each soil lift to rebuild and vegetate eroded streambanks.

Applications and Effectiveness

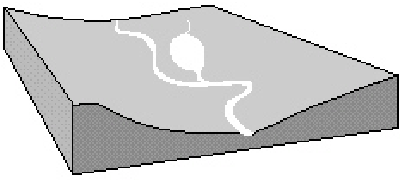
- Quickly establish riparian vegetation if properly designed and installed.
- Can be installed on a steeper and higher slope and has a higher initial tolerance of flow velocity than brush layering.
- Can be complex and expensive.
- Produce a newly constructed, well-reinforced streambank.
- Useful in restoring outside bends where erosion is a problem.
- Capture sediment and enhances conditions for colonization of native species.
- Slope stability analyses are recommended.
- Can be expensive.
- Require a stable foundation.

For More Information

- Consult the following references: Nos. 10, 11, 14, 21, 34, 56, 65, 77.

WATER MANAGEMENT

Sediment Basins



Barriers, often employed in conjunction with excavated pools, constructed across a drainage way or off-stream and connected to the stream by a flow diversion channel to trap and store waterborne sediment and debris.

Applications and Effectiveness

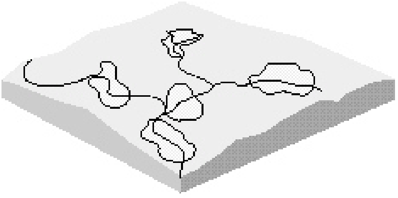
- Provide an interim means of reducing the sediment load from a stream.
- Used occasionally to sort sediment sizes.
- Temporarily reduce excessive sediment loads until the upstream watershed can be protected from accelerated erosion.
- Can also be used to separate out sediment which may be causing damages downstream along reaches which are incapable of transporting the sediment sizes.
- Can be integrated with more permanent stormwater management ponds.
- Can only trap the upper range of particle sizes (sand and gravel) and allow finer particles (silt and clay) to pass through.
- Require a high level of analysis.
- Require periodic dredging and other maintenance.

For More Information

- Consult the following references: Nos. 10, 13, 29, 45, 49, 69, 74, 80.

WATER MANAGEMENT

Water Level Control



Managing water levels within the channel and adjoining riparian zone to control aquatic plants and restore desired functions, including aquatic habitat.

Applications and Effectiveness

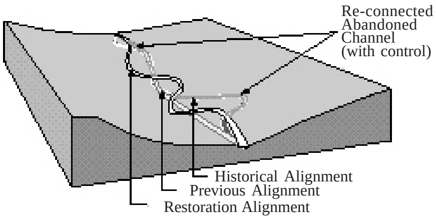
- Appropriate where flow depth in the stream, adjoining wetland, or the interdependent saturation zone in the adjoining riparian area is insufficient to provide desired functions.
- Need will often vary by season and requires flexible control devices which can be managed accordingly.
- The complexities of maintaining sediment balances, temperature elevation, change in channel substrate, changes in flow regime, and a host of other considerations must be factored into planning and design.
- Requires a high level of analysis.

For More Information

- Consult the following references: Nos. 11, 13, 15, 69, 75.

CHANNEL RECONSTRUCTION

Maintenance of Hydraulic Connections



Maintenance of hydraulic connectivity to allow movement of water and biota between the stream and abandoned channel reaches.

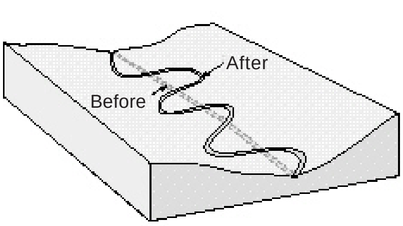
Applications and Effectiveness

- Used to prevent losses of aquatic habitat area and diversity.
- Slackwater areas adjoining the main channel have potential for spawning and rearing areas for many fish species and are a key component of habitat for wildlife species that live in or migrate through the riparian corridor.
- Recreation value can be enhanced if connecting channels are deep enough for small boats or canoes.
- Effective along reaches of realigned channel where cutoffs have been made.
- Not effective in streams with insufficient stages or discharges to maintain satisfactory hydraulic connections to the abandoned channel reaches.
- May require maintenance if sedimentation is a problem.
- May have limited life.
- Require a high level of analysis.

For More Information

- Consult the following references: Nos. 15, 56, 69, 75.

Stream Meander Restoration



Transformation of a straightened stream into a meandering one to reintroduce natural dynamics improve channel stability, habitat quality, aesthetics, and other stream corridor functions or values.

Applications and Effectiveness

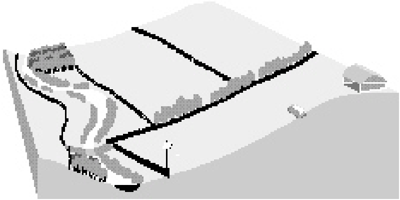
- Used to create a more stable stream with more habitat diversity.
- Requires adequate area where adjacent land uses may constrain locations.
- May not be feasible in watersheds experiencing rapid changes in land uses.
- Streambank protection might be required on the outside of bends.
- Significant risk of failure.
- Requires a high level of analysis.
- May cause significant increases in flood elevations.
- Effective discharge should be computed for both existing and future conditions, particularly in urbanized watersheds.

For More Information

- Consult the following references: Nos. 13, 16, 22, 23, 24, 46, 47, 52, 53, 54, 56, 61, 72, 75, 77, 78, 79, 86.

STREAM CORRIDOR MEASURES

Livestock Exclusion or Management



Fencing, alternate sources of water and shelter, and managed grazing to protect, maintain, or improve riparian flora and fauna and water quality.

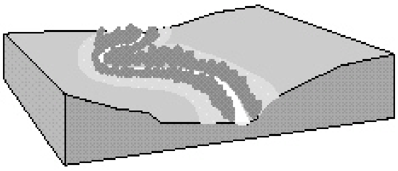
Applications and Effectiveness

- Appropriate where livestock grazing is negatively impacting the stream corridor by reducing growth of woody vegetation, decreasing water quality, or contributing to the instability of streambanks.
- Once the system has recovered, rotational grazing may be incorporated into the management plan.
- Must be coordinated with an overall grazing plan.

For More Information

- Consult the following references: Nos. 18, 39, 73.

Riparian Forest Buffers



Streamside vegetation to lower water temperatures, provide a source of detritus and large woody debris, improve habitat, and to reduce sediment, organic material, nutrients, pesticides and other pollutants migrating to the stream.

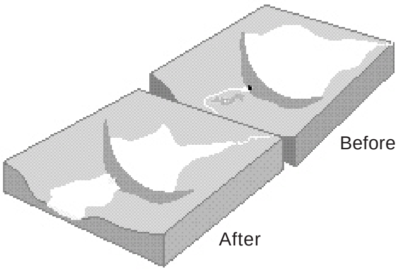
Applications and Effectiveness

- Applicable on stable areas adjacent to permanent or intermittent streams, lakes, ponds, wetlands and areas with ground water recharge.
- Unstable areas such as those with high surface erosion rates, mass soil movement, or active gullies will require stabilization prior to establishment of riparian forest buffers.
- Tolerant plant species and supplemental watering may be needed in some areas.
- Sites in arid and semi-arid regions may not have sufficient soil moisture throughout the growing season to support woody plants.
- Concentrated flow erosion, excessive sheet and rill erosion, or mass soil movement must be controlled in upland areas prior to establishment of riparian forest buffers.

For More Information

- Consult the following references: Nos. 20, 34, 49, 51, 70, 78, 79, 81, 82, 88, 89.

Flushing for Habitat Restoration



A high-magnitude, short duration release from a reservoir to scour fine-grained sediments from the streambed and restore suitable instream habitat.

Applications and Effectiveness

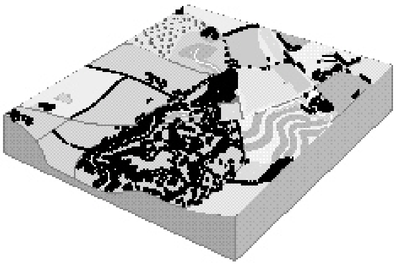
- Appropriate as part of an overall watershed management plan.
- May cause flooding of old floodplains below dams, depletion of gravel substrates, and significant changes in channel geometry.
- Flushing of fine sediments at one location may only move the problem further downstream.
- Seasonal discharge limits, rate of change of flow, and river stages downstream of impoundment should be considered to avoid undesirable impacts to instream and riparian habitat.
- Can be effective in improving gradation of streambed materials, suppression of aquatic vegetation, and maintenance of stream channel geometry necessary for desired instream habitat.
- Can induce floodplain scouring to provide suitable growing conditions for riparian vegetation.
- Requires high level of analysis to determine necessary release schedule.
- May not be feasible in areas where water rights are fully allocated.

For More Information

- Consult the following references: Nos. 11, 13, 32, 35, 41, 45, 57, 61, 73, 74, 81.

WATERSHED MANAGEMENT

Best Management Practices: Agriculture



Individual and systematic approaches aimed at mitigating non-point source pollution from agricultural land.

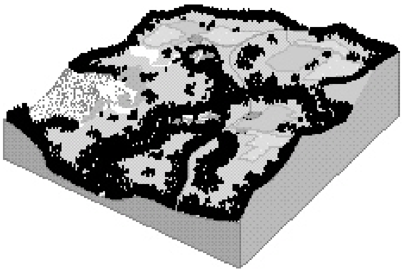
Applications and Effectiveness

- Used where current management systems are causing problems on-site or within farm or field boundaries and have a high potential to impact the stream corridor.
- Also applied where watershed management plans are being implemented to improve environmental conditions.
- Must fit within a comprehensive farm management plan, a watershed action plan, or a stream corridor restoration plan.
- Should consider the four season conservation of the soil, water, and microbial resources base.
- Tillage, seeding, fertility, pest management, and harvest operations should consider environmental qualities and the potential to use adjacent lands in water and soil conservation and management and pest management.
- Grazing land management should protect environmental attributes, including native species protection, while achieving optimum, long-term resource use.
- Where crops are raised and the land class allows, pastures should be managed with crop rotation sequences to provide vigorous forage cover while building soil and protecting water and wildlife qualities.
- Orchards and nursery production should actively monitor pest and water management techniques to protect ecosystem quality and diversity.
- Farm woodlots, wetlands, and field borders should be part of an overall farm plan that conserves, protects, and enhances native plants and animals, soil, water, and scenic qualities.
- BMPs may include: contour farming, conservation tillage, terracing, critical area planting, nutrient management, sediment basins, filter strips, waste storage management, and integrated pest management.

For More Information

- Consult the following references: Nos. 73, 78, 81.

Best Management Practices: Forestland



Individual and systematic approaches for mitigating non-point source pollution from forestland.

Applications and Effectiveness

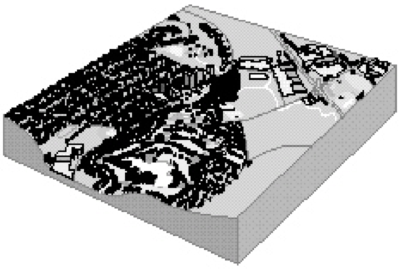
- Used where current management systems are causing problems in the watershed and have a high potential to impact the stream corridor.
- Also applied where management plans are being implemented to restore one or more natural resource functions in a watershed.
- Must consider how it fits within a comprehensive forestland management plan, a watershed action plan, or a stream corridor restoration plan.
- BMPs may include: preharvest planning, streamside management measures, road construction or reconstruction, road management, timber harvesting, site preparation and forest generation, fire management, revegetation of disturbed areas, forest chemical management, and forest wetland management.

For More Information

- Consult the following references: Nos. 9, 20, 27, 30, 34, 42, 49, 51, 70, 78, 79, 81, 82, 83, 88, 89.

WATERSHED MANAGEMENT

Best Management Practices: Urban Areas



Individual or systematic approaches designed to offset, reduce, or protect against the impacts of urban development and urban activities on the stream corridor.

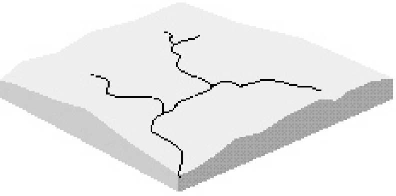
Applications and Effectiveness

- Used to improve and/or restore ecological functions which have been impaired by urban activities.
- Needs to be integrated with BMPs on other lands in the landscape to assure that stream restoration is applied along the entire stream corridor to the extent possible.
- The use of individual urban BMPs should be coordinated with an overall plan for restoring the stream system.
- Urban sites are highly variable and have a high potential for disturbance.
- Applicability of the treatment to the site situation in terms of physical layout, relationship to the overall system, arrangements for maintenance, and protection from disturbances are often critical considerations.
- BMPs may include: extended detention dry basins, wet ponds, constructed wetlands, oil-water separators, vegetated swales, filter strips, infiltration basins and trenches, porous pavement, and urban forestry.

For More Information

- Consult the following references: Nos. 29, 34, 43, 49, 78, 80, 81, 83.

Flow Regime Enhancement



Manipulation of watershed features (such as changes in land use or construction of impoundments) for the purpose of controlling streamflow and improving physical, chemical and biological functions.

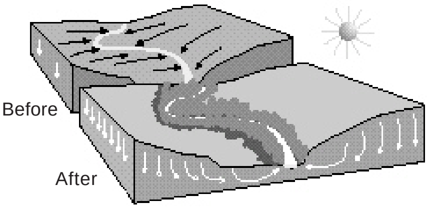
Applications and Effectiveness

- Appropriate where human-induced changes have altered stream flow characteristics to the extent that streams no longer support their former functions.
- Can restore or improve threatened functions (e.g., substrate materials or distribution of flow velocities to support the natural food web).
- Can require extensive changes over broad areas involving many land users.
- Can be expensive.
- Has been used for remediation of depleted dissolved oxygen levels, reduction in salinity levels, or to maintain a minimum flow level for downstream users.
- Must determine what impacts from historical changes in the flow regime over time can be mitigated using flow enhancement techniques.

For More Information

- Consult the following references: Nos. 32, 39, 45, 57, 75, 81.

Streamflow Temperature Management



Streamside vegetation and upland practices to reduce elevated streamflow temperatures.

Applications and Effectiveness

- Effective for smaller streams where bank vegetation can provide substantial shading of the channel and on which much of the canopy has been removed.
- Appropriate practices are those that establish streamside vegetation, increase vegetative cover, increase infiltration and subsurface flow, maintain base flow, and reduce erosion.
- Turbid water absorbs more solar radiation than clear; therefore, erosion control in watersheds can help in reducing thermal pollution.
- Flow releases from cooler strata of reservoirs must be exercised with caution. Although cooler, water from this source is generally low in dissolved oxygen and must be aerated before discharging downstream. Selective mixing of the reservoir withdrawal can moderate temperature as may be required.
- There might be opportunities in irrigated areas to cool return flows prior to discharge to streams.

For More Information

- Consult the following references: Nos. 32, 39, 45, 73, 80, 81, 88, 89.

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APPENDIX B

INCH-POUND / METRIC CONVERSION FACTORS

Length

Unit of measure	Abbreviation	mm	cm	m	km	in	ft	mi
millimeter	mm	1	0.1	0.001	—	0.0394	0.003	—
centimeter	cm	10	1	0.01	—	0.394	0.033	—
meter	m	1000	100	1	0.001	39.37	3.281	—
kilometer	km	—	—	1000	1	—	3281	0.621
inch	in	25.4	2.54	0.0254	—	1	0.083	—
foot	ft	304.8	30.48	0.305	—	12	1	—
mile	mi	—	—	1609	1.609	—	5280	1

Area

Unit of measure	Abbreviation	m^2	ha	km^2	ft^2	acre	mi^2
square meter	m^2	1	—	—	10.76	—	—
hectare	ha	10000	1	0.01	107600	2.47	0.00386
square kilometer	km^2	$1x10^6$	100	1	—	247	0.386
square foot	ft^2	0.093	—	—	1	—	—
acre	acre	4050	0.405	—	43560	1	0.00156
square mile	mi^2	—	259	2.59	—	640	1

Volume

Unit of measure	Abbreviation	km^3	m^3	L	Mgal	acre-ft	ft^3	gal
cubic kilometer	km^3	1	1x10 9	—	—	811000	—	—
cubic meter	m^3	—	1	1000	—	—	35.3	264
liter	L	—	0.001	1	—	—	0.0353	0.264
million U.S. gallons	Mgal	—	—	—	1	3.07	134000	$1x10^6$
acre-foot	acre-ft	—	1233	—	0.3259	1	43560	325848
cubic foot	ft^3	—	0.0283	28.3	—	—	1	7.48
gallon	gal	—	—	3.785	—	—	0.134	1

Flow Rate

Unit of measure	Abbreviation	km^3 /yr	m 3 /s	L/s	mgd	gpm	cfs	acre-ft/day
cubic kilometers/year	km^3 /yr	1	31.7	—	723	—	1119	2220
cubic meters/second	m^3 /s (m^3 /sec)	0.0316	1	1000	22.8	15800	35.3	70.1
liters/second	L/s (L/sec)	—	0.001	1	0.0228	15.8	0.0353	0.070
million U.S. gallons/day	mgd (Mgal/d)	—	0.044	43.8	1	694	1.547	3.07
U.S. gallons/minute	gpm (gal/min)	—	—	0.063	—	1	0.0022	0.0044
cubic feet/second	cfs (ft^3 /s)	—	0.0283	28.3	0.647	449	1	1.985
acre-feet/day	acre-ft/day	—	—	14.26	0.326	226.3	0.504	1

Temperature

Unit of measure	Abbreviation	F	C
Fahrenheit	F	—	.56 (after subtracting 32)
Celsius	C	1.8 (then add 32)	—

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PART III

STREAM CORRIDOR RESTORATION

In Italia, nella gestione dei corsi d'acqua, prevale ancora un approccio ingegneristico strettamente monodisciplinare; la rinaturazione degli ambienti fluviali è propugnata da pochi, considerati con sufficienza come utopisti o sognatori. Perfino l'ingegneria naturalistica, sebbene volta a sostituire il cemento con vegetali vivi, è ancora applicata essenzialmente per le sue funzioni di consolidamento, con scarsa attenzione alle funzioni naturalistiche ed è spesso ridotta al mero ruolo di cosmetico ambientale di opere idrauliche, per altri versi devastanti.

Il principale ostacolo al superamento di questo approccio è la diffusa arretratezza culturale, che inchioda i progettisti idraulici alla comoda inerzia delle tecniche ingegneristiche tradizionali.

Con la pubblicazione del volume *Stream Corridor Restoration*, il CISBA intende scuotere la pigrizia dei progettisti, mettere allo scoperto i profondi limiti delle pratiche attuali e mostrare la ricchezza culturale di un approccio interdisciplinare che fornisce a ciascuno stimoli di crescita professionale.

Il volume, redatto da 15 agenzie governative americane con la collaborazione dei più autorevoli esperti di numerose discipline, presenta i principi e la pratica del ripristino dei corridoi fluviali.

Per la completezza della trattazione, il ricco e curato corredo d'illustrazioni, l'autorevolezza delle fonti, l'utilità dei consigli pratici, degli approfondimenti, dei casi-studio, il volume rappresenta un prezioso contributo all'affermazione di una cultura della riqualificazione fluviale nel nostro paese. (Parte 3 di 3)