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Guidance for
Federal Land Management
in the Chesapeake Bay Watershed

Chapter 7. Hydromodification

Nonpoint Source Pollution
Office of Wetlands, Oceans, and Watersheds
U.S. Environmental Protection Agency

Chapter 7. Hydromodification

Contents

1 Overview

The Chesapeake Bay and its tributaries, representing the nation's largest estuary, is a resource of important economic, social and environmental significance. The Chesapeake Bay ecosystem, however, remains severely degraded primarily because of pollution from excess nitrogen (N), phosphorus (P), and sediment, which enters surface waters. Those pollutants come from multiple diverse sources within the Chesapeake Bay watershed, but the primary sources are agriculture, urban and suburban runoff, wastewater, and airborne contaminants (Chesapeake Bay Program 2009). Another contributor of pollutants to the Chesapeake Bay is hydromodification. The states in the U.S. Environmental Protection Agency's (EPA's) Region 3 report in their biennial water quality report that a cumulative total of 1,427 miles of assessed rivers and streams, 1,687 acres of assessed lakes and reservoirs, and 1,916 square miles of assessed bays and estuaries in the mid-Atlantic are impaired by hydromodification.

The term *hydromodification* as used in this guidance refers to the alteration of the hydrologic characteristics of waterbodies, which in turn could cause degradation of water resources. Many activities that are considered forms of hydromodification have been conducted and continue to be conducted because they are considered to be critical to human activities, such as dredging shipping channels for commerce or constructing culverts at stream crossings for transportation. Hydromodification can also refer to activities that are conducted in and adjacent to stream channels to maintain stream functions or reduce damage to streams or adjacent properties such as clearing of debris or armoring of streambanks.

While hydromodification activities likely occurred within the Chesapeake Bay watershed before European settlement (e.g., fish traps, secondary effects from riparian agriculture) the scale and scope of hydromodification increased dramatically with the advent of European expansion on the east coast of North America. Early settlers constructed dams to harness hydropower and drained floodplain areas for farming (Walter and Merritts 2008; Schenk and Hupp 2009). As development accelerated through the colonial, post revolutionary and industrial periods hydromodification activities expanded to include dredging of natural and man-made waterways for commerce, construction of water supply, recreational and flood control dams, and channel straightening and dredging for flood control and agriculture. In more recent years, development of the built environment has resulted in secondary channel erosion within and downstream of urban centers.

1.1 Sources

Hydromodification activities are grouped into three general categories for the purposes of this chapter: (1) channelization and channel modification, (2) dams, and (3) streambank and shoreline erosion. Such broad categories are useful in that they provide a logical organization for hydromodification activities. However, as is described later in this chapter, implementation measures and practices can apply across these three activity categories. In addition certain hydromodification activities might not fit neatly within any of the three categories.

1.1.1 Streambank and Shoreline Erosion

Streambank and shoreline erosion refers to the degradation of stream, estuary, and lake shore areas resulting in loss of soil and other material landward of the bank along nontidal streams and rivers. Streambank erosion occurs when the sediment on streambanks detaches and becomes mobilized within or near the stream channel. Detachment is a complex process resulting from the interaction of streamflow, vegetation, cohesive properties of soil, and the soil water interface. Eroded material is often carried downstream and re-deposited in the channel bottom or in point bars along bends in the waterway. Shoreline erosion occurs in large, open waterbodies, such as larger lakes and the lower estuarine portion of the Chesapeake Bay, where waves and currents sort coarser sands and gravel from eroded banks and move them in both directions along the shore away from the area being eroded. While the underlying forces causing the erosion could be different for streambank and shoreline erosion, the results, erosion and its impacts are usually similar. It is also important to note that streambank and shoreline erosion are natural processes and that natural background levels of erosion also exist and might be necessary to ensure the health of a particular stream. However, human activities along or adjacent to streambanks or shorelines can accelerate erosion and other nonpoint sources of pollution.

In both urban and rural areas, streambank erosion is often associated with changing land use characteristics within a watershed such as increased impervious surfaces. Because the erosion of streambanks and shorelines is often closely related to upland activities that occur outside riparian areas, it is often necessary to consider solutions to these issues as a component of overall watershed protection and restoration objectives. The topic of upland effects on stream channels is covered in more detail in the Urban and Suburban chapter of this guidance.

1.1.2 Channelization

Channelization and channel modification include activities such as straightening, widening, deepening, and clearing channels of debris and accumulated sediment. Objectives of channelization and channel modification projects include flood control, infrastructure protection, channel and bank stabilization, habitat improvement/enhancement, recreation, and flow control for water supply (source). Channelization activities play an important role in nonpoint source pollution in the Chesapeake Bay by affecting the timing and delivery of pollutants that enter the water. Channelization can also be a cause of higher flows during storm events, which increases the risk of flooding.

Historically, channelization occurred to reduce flooding, drain wet areas for agriculture and to allow for commerce among, other reasons. In recent years, however, regulatory requirements primarily driven by the Clean Water Act have limited traditional hydromodification activities within stream channels and waterbodies. Simultaneously, water resource managers have recognized the critical role that healthy stable stream corridors play in the protection and improvement of water quality and living resources within the Chesapeake Bay. As a result, many of the hydromodification activities occurring are those related to maintenance and restoration of channel corridors and shorelines.

1.1.3 Dams and In-Stream Structures

Dams and in-stream structures are artificial barriers on waterbodies that control the flow of water. Such structures can be built for a variety of purposes, including flood control, power generation, irrigation, navigation, and to create ponds, lakes, and reservoirs for uses such as municipal water supply, fish farming, and recreation. While these types of structures are constructed to provide benefits to society, they can contribute to nonpoint source pollution and have detrimental effects on living resources. For example, dams can alter flows that ultimately can cause effects on water quality and roadway culverts can result in the scour of stream sediments at their outlet. While the structures were often built for purposes related to human needs, in many cases that need is no longer present (e.g., small hydropower dams to support manufacturing). As a result, water resource managers have conducted detailed cost benefit analysis at many dams, and the results often show that the benefits of dam removal outweigh the benefits of continuing to maintain and operate the dam.

An important development in the effect of dams in water quality is the increasing trend of dam removal within the Chesapeake Bay. As dams reach their life expectancy, many will be removed for safety concerns or to restore the connectivity of aquatic ecosystems. This phenomenon is covered extensively in one of the practices (Legacy effects of Dams and Dam Removal) recommended in Section 3 of this chapter.

1.2 Contribution to Nonpoint Source Pollution in Chesapeake Bay

The contribution of hydromodification activities to sediments and nutrient loads to the Chesapeake Bay is poorly defined in the current research literature. Traditionally, land use managers and water resources professionals categorized nonpoint source pollutant loadings based on specific land uses (such as agricultural, urban and silviculture). Contribution of specific hydromodification activities such as channel erosion or dams is less well defined. With recent research on the topic, however, increased attention and research activity has been focused on separating the contribution of specific activities such as stream corridor instability to the overall pollutant loading to the Bay.

The interaction between pollutants from upland sources and those that originate within the stream corridor is a complex relationship in which in-stream transported pollutants are often affected by historic or current upland activities. During the 1700s and 1800s eroding upland agricultural areas resulted in significant sediment storage within stream corridors typically called *legacy* sediment (USGS 2003). The construction of mill dams during that period resulted in the impoundment and storage of sediment behind tens of thousands of mill dams in the mid-Atlantic region. Subsequent removal of these dams during the late industrial period and urban and suburban development in the past 100 years has led to remobilization of the legacy sediments as stream corridors have become instable and streambanks have eroded (USGS 2003).

Because of the intimate nature of hydromodification activities with the stream corridor, there is understandably a close relationship between those activities and sediment delivery to surface waters. A summary of existing information of the impacts of stream hydromodification on the quality of the Chesapeake Bay is provided in Table 7-1. These studies demonstrate the importance of stream restoration and protection in achieving pollutant reduction in the Chesapeake Bay, particularly for sediment and the P that accompanies sediment loading.

While the contribution of sediment from streambank erosion might be a significant source in many streams, the percentage of *unstable* streams within the Chesapeake Bay watershed is unknown (USGS 2003).

The contribution of hydromodification to other pollutants of concern in the Chesapeake Bay is even less well documented. N contribution throughout the watershed is primarily from agricultural, wastewater, and airborne sources. N in its most commonly observed forms is present in very low levels within contributions from hydromodification sources. P on the other hand, given its tendency to become soil and particulate bound, is often present in the legacy sediments, which are significant contributors to eroding streams.

Table 7-1. Studies quantifying the impact of sediment loading from stream hydromodification on Chesapeake Bay water quality

Study	Findings
A Summary Report of Sediment Processes in Chesapeake Bay and Watershed, USGS, Water-Resources Investigations Report 03-4123, 2003	Summarizes the impacts and sources of sediment and notes that sediment yield from urbanized areas can remain high after active construction is complete because of increased stream corridor erosion due to altered hydrology
Schueler et.al. 2000. *The Practice of Watershed Protection, Technical Note #119 from Watershed Protection Techniques 3(3):729-734*, Center for Watershed Protection, 2000.	Stream enlargement, and the resulting transport of excess sediment, is caused by urban development
U.S. Environmental Protection Agency. 2001. Protecting and Restoring America's Watersheds: Status, Trends, and Initiatives in Watershed Management, EPA 840-R-00-001. www.epa.gov/owow/protecting/restore725.pdf.	Straightened and channelized streams carry more sediments and other pollutants to their receiving waters. Up to 75% of the transported sediment from the Pocomoke watershed on the Eastern Shore of Maryland was found to be erosion from within the stream corridor
Gellis et al. *Synthesis of U.S. Geological Survey Science for the Chesapeake Bay Ecosystem and Implications for Environmental Management, Chapter 6: Sources and Transport of Sediment in the Watershed*. 2007, U.S. Geological Survey Circular 1316.	Sediment sources are throughout the Chesapeake Bay watershed, with more in developed and steep areas
Gellis et al. 2009, *Sources, transport, and storage of sediment in the Chesapeake Bay Watershed: U.S. Geological Survey Scientific Investigations Report* 2008–5186	In the Piedmont region, streambank erosion was a major source of sediment in developed Little Conestoga Creek; 30% of sediment from the Mattawoman Watershed on the Coastal Plain (flat land) is from streambanks
Devereux et al. Suspended-sediment sources in an urban watershed, Northeast Branch Anacostia River, Maryland. Hydrological Processes, Accepted 2009.	Streambank erosion was the primary source of sediment in the Northeast Branch Anacostia River

2 Chesapeake Bay Hydromodification Implementation Measures

In 2007 EPA published a guidance document titled *National Management Measures to Control Non-point Source Pollution from Hydromodification* whose purpose was to provide background information on nonpoint source pollution and to offer a variety of solutions for reducing nonpoint source pollution resulting from hydromodification. Background information includes a discussion of the sources of nonpoint source pollution and mechanisms for transport into the nation's waters. The guidance further presents a series of *Management Measures* for use on a national scale to directly address the causative factors for nonpoint source pollution. Management measures as presented in the 2007 document establish performance expectations and, where appropriate, specific actions that can be taken to prevent or minimize nonpoint source pollution.

A series of practices was also described for each management measure. Practices are specific actions taken to achieve, or help achieve, a management measure. Practices are often termed best management practices (BMPs); however, the word best was dropped from the 2007 hydromodification guidance and will not be used in this chapter because the use of the adjective is too subjective.

This chapter expands on the extensive resources provided in the 2007 document while focusing on the pollutants, sources, and practices considered important to the overall goal of restoring the health of the Chesapeake Bay. Implementation measures (formerly management measures) presented are either the same or improved versions of those presented in the 2007 guidance. Where available, information on the application, design, and performance of specific practices suitable for use in the Chesapeake Bay are provided. To support one of the key steps required by the Executive Order 13508 to define *next generation* tools, a number of practices have been added to this chapter, which exhibit proven capability to address the nonpoint source issues within the Chesapeake Bay. This chapter and the 2007 guidance are intended to be used in tandem to provide the reader with an updated summary of tools and techniques appropriate for addressing nonpoint source pollution in the Chesapeake Bay.

2.1 General Principles and Goals

The purpose of this chapter is to provide the user with background information on how hydromodification activities affect nutrient and sediment impacts within the Chesapeake Bay and to provide guidance on a range of practices that can be implemented to reduce the impact of hydromodification activities on Bay water quality. While this chapter focuses on practices that are relevant to the Chesapeake Bay and its associated watershed specifically, the information provided is also widely relevant wherever hydromodification activities result in degradation of surface waters.

While the primary focus of this chapter is on reducing loading of sediment, N, and P, it is important to note that there are often numerous secondary benefits to each specific practice detailed herein. To that end, appropriate additional information is provided on secondary benefits such as those associated with living resources (and complementing the activities suggested in draft report 202(g) of Executive Order 13508). For example, bioengineering techniques such as live staking and brush mattressing are typically applied to an eroding streambank principally to reduce sediment loading to the associated stream. However, the function of those practices is based on establishing riparian vegetation, which is an important component in improving aquatic riparian habitat.

For many hydromodification activities and their associated effects, a close relationship exists to other chapters of this guidance. In such cases, the reader might be directed to the respective section for additional guidance. For instance, increased rate and volume of stormwater runoff from urbanizing areas often leads to channel and streambank erosion. In that case, the causative factor of the effect (urbanization) is covered in the urban section of this chapter. Because streambank erosion is itself considered a form of hydromodification, the effect is described in detail and number of structural practices recommended to address the effect within the stream corridor.

While this chapter recommends a series of approaches and information on specific tools and techniques to address nonpoint source pollution in the Chesapeake Bay watershed on a project basis, each project must be considered within the context of the watershed or subwatershed in which it is prescribed. The successful implementation of watershed restoration requires that projects be identified and selected consistent with watershed assessments and prioritized according to the overall watershed restoration goals (Beechie et al. 2008). Furthermore, individual projects should be considered as a component of watershed restoration and measured according to the cumulative benefits of other similar watershed restoration projects that might be proposed (Kondolf et al. 2008).

2.2 Implementation Measures

To accomplish the goals set forth above, this chapter suggests a series of implementation measures that are recommended to address the effects of hydromodification. The reader might notice that the 2007 guidance document includes six *Management Measures* that tribal, state, or local programs could implement to address nonpoint source pollution from hydromodification activities. In this chapter, the six management measures have been reduced to five categories and renamed implementation measures. That terminology is used in this chapter because they are measures that can be implemented to address specific functional causes of impacts of hydromodification activities.

Implementation Measures:

H-1. Protect Streambanks and Shorelines from Erosion
H-2. Control Upland Sources of Sediment and Nutrients at Dams
H-3. Restore In-stream and Riparian Habitat Function
H-4. Reduce Pollutant Sources through Operational and Design Management
H-5. Restore Stream and Shoreline Physical Characteristics

2.2.1 Implementation Measure H-1: Protect Streambanks and Shorelines from Erosion

Implementation Measure H-1:

The protection of streambanks and shorelines from erosion refers to the installation of structural or biological practices at or near the land water interface. The primary goals of this implementation measure are the following:

1. Protect streambank and shoreline features with the potential to reduce nonpoint source pollution
2. Protect streambanks and shorelines from erosion from uses of either the shorelands or adjacent surface waters

Implementation Measure H-1 focuses on preserving stable streambanks and shorelines to limit the loss of pollutants, most notably sediment, from the erosion at the land water interface. This measure is most closely related with Management Measure 6 of the 2007 guidance (Eroding Streambanks and Shorelines). Practices appropriate for addressing Implementation Measure H-1 consist of both structural practices such as riprap as well as management practices such as non-eroding roadways. Where possible, the practitioner should consider the protection of streambanks and shoreline within the context of overall watershed goals and select practices that address multiple watershed objectives where possible.

The application of bioengineering stream armoring techniques, which use vegetation and natural systems, to address erosion for instance, should be considered before implementing more rigid, structural controls such as riprap. While bioengineering techniques might not be suitable for all applications, they often support the objectives of other implementation measures and overall watershed goals.

Practices

The practices noted in Table 7-2 are suggested as appropriate to address Implementation Measure H-1 and are described in more detail in Section 3 of this chapter. The table categorizes practices according to whether they were detailed in the previous guidance, updated within this chapter, or identified as a next generation tool or technique for addressing nonpoint source pollution in Chesapeake Bay. Updated practices are those that are described in detail in the 2007 guidance but have updated or region-specific information in Section 3. Next generation tools and techniques are those newer practices that had not been previously identified as appropriate for addressing Implementation Measure H-1 but are described in detail in Section 3.

Table 7-2. Practices appropriate for use in addressing Implementation Measure H-1

Practice	Described in 2007 guidance?	Updated?	Next generation tools and techniques?	Page
Breakwaters	Yes			
Bulk Heads and Seawalls	Yes			
Groins	Yes			
Multi-Cell Culverts			Yes	7-53
Non-Eroding Roadways	Yes	Yes		7-60
Return Walls	Yes			
Rip Rap	Yes	Yes		7-68
Toe Protection	Yes	Yes		7-77

Note: Clicking this link will access the 2007 document (*National Management Measures to Control Non-point Source Pollution from Hydromodification*). To find a specific practice, use the bookmarks.

2.2.2 Implementation Measure H-2: Control Upland Sources of Sediment and Nutrients at Dams

Implementation Measure H-2:

The control of upland sources of nonpoint source pollutants at dams and other hydromodification facilities refers to the active implementation of pollutant control techniques and practices that minimize the source generation and reduce the transport of sediments and nutrients into the Chesapeake Bay and its watershed. This implementation measure is well described in the 2007 guidance document (formerly titled *Erosion and Sediment Control for Construction of New Dams and Maintenance of Existing Dams*). The goals of this implementation measure are

1. Reduce the generation of sediment and nutrients during and after construction
2. Retain eroded sediment and nutrients on-site
3. Apply nutrients at rates necessary to establish and maintain vegetation without causing significant nutrient runoff to surface waters

Implementation Measure H-2 is identical to Management Measure 3 from the 2007 hydromodification guidance. No updated information is provided on this measure whose purpose is to prevent sediment and nutrients from entering surface waters during the construction or maintenance of dams. Because of the extensive environmental permitting necessary for the construction of dams in the Chesapeake Bay watershed and the developed nature of the region’s water resources, it is unlikely that significant dam construction will occur in the near future. Maintenance of existing dams and impoundments, therefore, is likely to be the most significant activity to which this measure is applicable.

No updated design or performance information is available for the practices recommended for this implementation measure. As a result, for more information on specific practices, see the 2007 hydromodification guidance.

Practices

The practices noted in Table 7-3 are suggested as appropriate to address Implementation Measure H-2.

Table 7-3. Practices appropriate to addressing Implementation Measure H-2

Practice
Check Dams
Coconut Fiber Roll
Construction Runoff Intercepts
Construction Management
Erosion Control Blankets
Locate Potential Land Disturbing Activities away from Critical Areas
Mulching
Preserve Onsite Vegetation
Phase Construction
Retaining Walls
Revegetate
Project Scheduling
Sediment Basin/Rock Dams
Sediment Fences
Sediment Traps
Seeding
Site Fingerprinting
Sodding
Soil Protection
Surface Roughening
Training ESC
Wildflower Cover

Note: Clicking this link will access the 2007 document (*National Management Measures to Control Non-point Source Pollution from Hydromodification*). To find a specific practice, use the bookmarks.

2.2.3 Implementation Measure H-3: Restore In-Stream and Riparian Habitat Function

Implementation Measure H-3:

The restoration of in-stream and riparian habitat function refers to the direct implementation of practices that address functions of the aquatic environment. Because the practices recommended as part of this implementation measure often do not address the causative factors behind habitat degradation, other implementation measures described in this chapter should be considered for implementation. This implementation measure is well described in the 2007 guidance document (titled *Protection of Surface Water Quality and In-stream and Riparian Habitat*). The primary goal of this implementation measure is

1. Provide for safe passage of fish and other aquatic species upstream or downstream of dams and other structures

Physical structures that block or impede fish migrations to historic spawning habitats have been identified as potentially the most important factor in the decline in migratory fish such as American shad, river herring, and the American eel. The removal of blockages or the installation of structures that encourage or enable fish passage such as fish lifts, fish ladders, and other passageways are important measures that can be implemented within the Chesapeake Bay to ensure that migratory fish are able to move freely throughout historical migratory routes. Approximately 1,924 miles of stream in the Chesapeake Bay watershed have been opened to fish passage, and Executive Order 13508 states that an additional 1,000 stream miles will be opened by implementing 100 priority dam-removal, fish-passage projects by 2025.

The restoration of in-stream and riparian habitat function is closely related to Implementation Measure H-5, Restore Stream and Shoreline Physical Characteristics, described below. The practices recommended for use to address Implementation Measure H-5 often directly support the primary goal of this implementation measure. EPA encourages practitioners to consider these two implementation measures and their respective practices as collaborative techniques to address nonpoint source pollution in the Chesapeake Bay and its effect on living resources.

Practices

The practices noted in Table 7-4 are suggested as appropriate to address Implementation Measure H-3 and are described in more detail in Section 3 of this chapter. The table categorizes practices according to whether they were detailed in the previous guidance, updated within this chapter, or identified as a next generation tool or technique for addressing nonpoint source pollution in Chesapeake Bay. Updated practices are those that are described in detail in the

2007 guidance but have updated or region-specific information in Section 3. Next generation tools and techniques are those newer practices that had not been previously identified as appropriate for addressing Implementation Measure H-3 but are described in detail in Section 3.

Table 7-4. Practices recommended to address Implementation Measure H-3

Practice	Described in 2007 guidance?	Updated?	Next generation tools and techniques?	Page
Behavioral Barriers	Yes			
Collection Systems	Yes			
Establish and Protect Stream Buffers	Yes	Yes		7-28
Fish Ladders	Yes			
Fish Lifts	Yes			
Legacy Effects of Dams and Dam Removal			Yes	7-37
Physical Barriers	Yes			
Riparian Improvements		Yes		7-66
Shoreline Sensitivity Assessment	Yes	Yes		7-72
Transfer of Fish Runs	Yes			
Vegetated Buffers	Yes	Yes		7-80
Vegetated Filter Strips	Yes	Yes		7-82

Note: Clicking this link will access the 2007 document (*National Management Measures to Control Non-point Source Pollution from Hydromodification*). To find a specific practice, use the bookmarks.

2.2.4 Implementation Measure H-4: Reduce Pollutant Sources through Operational and Design Management

Implementation Measure H-4:

Reduction of pollutant sources through operational and design management of dams refers to the design and management of dams so as to minimize the source generation and reduce the transport of sediments and nutrients into the Chesapeake Bay and its watershed. This implementation measure is well described in the 2007 guidance document (formerly titled *Erosion and Sediment Control for Construction of New Dams and Maintenance of Existing Dams*). The goals of this implementation measure are

1. Reduce pollutant generation and impact on living resources through programmatic dam management
2. Design structures to limit pollutant generation

Implementation Measure H-4 addresses pollutants resulting from operational activities at in-stream facilities such as dams and impoundments. The operation and management of such facilities typically has minimal impact on the delivery of nonpoint source pollutants to downstream waters. One notable exception is the removal of impoundments, which is covered in detail in Implementation Measure H-5 and in the practice: Legacy Effects of Dams and Dam Removal.

Operational practices do have significant implications on the living resources within and downstream of structures via their effect on other water quality parameters such as water temperature and dissolved oxygen. Management should focus on tools and techniques to reduce the impact of dam and in-stream structure operation on water quality through the management of physical flow processes to meet environmental criteria (Olden and Naimen 2010; Merritt et al. 2010).

Practices

The practices noted in Table 7-5 are suggested as appropriate to address Implementation Measure H-4 and are described in more detail in Section 3 of this chapter. The table categorizes practices according to whether they were detailed in the previous guidance, updated within this chapter, or identified as a next generation tool or technique for addressing nonpoint source pollution in Chesapeake Bay. Updated practices are those that are described in detail in the 2007 guidance but have updated or region-specific information in Section 3. Next generation tools and techniques are those newer practices that had not been previously identified as appropriate for addressing Implementation Measure H-4 but are described in detail in Section 3.

Table 7-5. Practices recommended as appropriate to address Implementation Measure H-4

Practice	Described in 2007 guidance?	Updated?	Next generation tools and techniques?	Page
Advanced Hydroelectric Turbines	Yes	Yes		7-22
Flow Augmentation	Yes	Yes		7-32
Selective Withdrawal	Yes	Yes		7-71
Turbine Operation	Yes	Yes		7-78
Turbine Venting	Yes	Yes		7-79

2.2.5 Implementation Measure H-5: Restore Stream and Shoreline Physical Characteristics

Implementation Measure H-5:

The restoration of stream and shoreline physical characteristics is important to restoring predevelopment hydrology and reducing loading from larger and scouring flows. Degraded streams can themselves become a source of downstream pollution, such as when P-laden sediments are mobilized during high-flow events. In such cases, stream restoration can be a useful strategy to improve downstream water quality. However, it is important to keep in mind that the elevated flows causing sediment mobilization must also be addressed (see the Urban and Suburban chapter). Stream stabilization requires restoration of the stream's energy signature. The predevelopment hydrology of the watershed must be restored to regain the predevelopment character of the stream; however, in existing urban areas, that might be a longer-term goal. The primary goal of this implementation measure is to

1. Restore stable relationship between watershed hydrology and stream and shoreline geometry. Where streambank or shoreline erosion is a nonpoint source pollution problem, streambanks and shorelines should be stabilized. Vegetative methods are strongly preferred unless structural methods are more effective, considering the severity of stream flow discharge, wave and wind erosion, offshore bathymetry, and the potential adverse effect on other streambanks, shorelines, and offshore areas.

Many methods have been developed to restore the physical characteristics of streams and shorelines to address lost function and instability. While many of the techniques can be applied in isolation to address specific physical characteristics, for instance installing root wad revetments to address bank erosion, EPA encourages practitioners to consider the practices listed below and detailed in Section 3 as components of an overall restoration strategy. It is important to note that restoration strategies should consider leveraging the natural characteristics of the stream and shoreline hydrology, geometry, and ecology to address physical function, such as biological engineering techniques, such as live fascines and brush layering in preference to techniques that rely on structural characteristics such as revetments. Where possible, measures should focus on the restoration of physical characteristics that are appropriate to overall watershed goals and future conditions.

Physical restoration can help to restore the natural ecosystem function of nutrient removal that occurs in streams. Studies that evaluate the N-removal ability of restored streams are summarized in Table 7-6.

Table 7-6. Studies evaluating the N removal ability of restored streams in the Chesapeake Bay watershed

Study	Finding
Kaushal et al. 2008. Effects of Stream Restoration on Denitrification in an Urbanizing Watershed. *Ecological Applications* 18(3):789–804.	Streams with ecological functions intact remove N at a much higher rate than degraded urban streams, and stream restoration practices can restore this N removal function
Klocker et al. *Nitrogen uptake and denitrification in restored and unrestored streams in urban Maryland, USA*. Aquatic Sciences, Accepted October 2009.	Degraded urban streams, deeply eroded and *disconnected* from their floodplain have substantially lower rates of N removal that than streams hydraulically connected to their riparian banks via low slopes, and reconnecting the stream to the floodplain can increase

In addition to the water quality improvements that can be achieved through stream restoration, the flood management community has become increasingly aware of the benefits of restoration in preventing flood damages. The Association of State Floodplain Managers (ASFPM) has prepared a white paper called *Natural and Beneficial Floodplain Functions: Floodplain Management—More than Flood Loss Reduction* (http://www.floods.org), which emphasizes the multiple benefits of protecting and restoring streams and their associated floodplains.

Techniques for stream and floodplain restoration are also described in the Riparian chapter of this guidance document. Example references for stream restoration and information on the impacts of urban runoff on stream ecosystems are provided in Table 7-7.

Table 7-7. References on urban stormwater effects on streams with emphasis on restoration and habitat

USDA Natural Resources Conservation Service, *Part 654 Stream Restoration Design National Engineering Handbook,* 210–VI–NEH, August 2007
Federal Interagency Stream Restoration Working Group (FISRWG) (1998*). Stream Corridor Restoration: Principles, Processes, and Practices*, ISBN-0-934213-60-7, Distributed by the National Technical Information Service at 1-800-533-6847.
Infiltration vs. Surface Water Discharge: Guidance for Stormwater Managers, Final Report. 03-SW-4, Water Environment Research Federation (WERF 2006) Appendix B. Assessment of Existing Watershed Conditions: Effects on Habitat.

Practices

The practices noted in Table 7-8 are suggested as appropriate to address Implementation Measure H-5 and are described in more detail in Section 3 of this chapter. The table categorizes practices according to whether they were detailed in the previous guidance, updated within this chapter, or identified as a next generation tool or technique for addressing nonpoint source pollution in the Chesapeake Bay. Updated practices are those that are described in detail in the

2007 guidance but have updated or region-specific information in Section 3. Next generation tools and techniques are those newer practices that had not previously been identified as appropriate for addressing Implementation Measure H-5 but are described in detail in Section 3.

Table 7-8. Practices recommended for addressing Implementation Measure H-5

Practice	Described in 2007 guidance?	Updated?	Next generation tools and techniques?	Page
Bank Shaping and Planting	Yes	Yes		7-23
Branch Packing	Yes			
Brush Layering	Yes			
Brush Mattressing	Yes	Yes		7-24
Cross Vanes			Yes	7-26
Dormant Post Planting	Yes			
Joint Planting	Yes	Yes		7-35
Legacy Effects of Dams and Dam Removal			Yes	7-37
Live Crib Walls	Yes	Yes		7-41
Live Fascines	Yes	Yes		7-43
Live Staking	Yes	Yes		7-46
Check Dams (Log & Rock)	Yes			
Marsh Creation and Restoration	Yes	Yes		7-51
Natural Channel Design and Restoration			Yes*	7-55
Revetements	Yes	Yes		7-64
Rock and Log Vanes			Yes	7-69
Root Wad Revetements	Yes			
Step Pools			Yes	7-73
Streambank Dewatering			Yes	7-75
Tree Revetements	Yes			
Vegetated Gabions	Yes	Yes		7-84
Vegetated Geogrids	Yes	Yes		7-85
Vegetated Reinforced Soil Slope (VRSS)	Yes	Yes		7-86
Weirs	Yes	Yes		7-87
Wing Deflectors	Yes	Yes		7-89

Note: Clicking this link will access the 2007 document (*National Management Measures to Control Non-point Source Pollution from Hydromodification*). To find a specific practice, use the bookmarks.

* This practice was originally named Rosgen's Stream Classification Method in the 2007 guidance document.

3 Chesapeake Bay Hydromodification Practices

The practices detailed in this section are suggested as appropriate for use in the Chesapeake Bay and nationally to address causative factors and impacts of hydromodification. While many of these practices were previously described in detail in the 2007 guidance document, some are new and represent the next generation of tools and actions to address nonpoint source pollution. For those practices described in the 2007 guidance and for which no additional information is relevant, the reader is directed to the earlier guidance. For those practices described previously and for which additional information is available, new information is presented; the reader is directed to refer to both this chapter and the 2007 guidance. For those practices that are not included in the earlier guidance and have been identified as appropriate for use in the Chesapeake Bay, detailed information is provided to describe the practice and discuss appropriate applications and purpose as well as information on practice costs and performance if available.

3.1 Existing Practices

The practices listed in Table 7-9 are described in detail in the 2007 National Hydromodification guidance document. For additional information on the practices, see that document. Limited additional information exists regarding these practices and their use in the Chesapeake Bay watershed.

Table 7-9. Practices described in the 2007 guidance document

Practice	IM1	IM2	IM3	IM4	IM5
Behavioral Barriers			X		
Branch Packing					X
Breakwaters	X				
Brush Layering					X
Bulkheads and Seawalls	X				
Check Dams		X			
Coconut Fiber Roll		X			
Collection Systems			X		
Construction Runoff Intercepts		X			
Construction Management		X			
Dormant Post Plantings					X
Erosion Control Blankets		X			
Fish Ladders			X		

Table 7-9. Practices described in the 2007 guidance document *(continued)*

Practice	IM1	IM2	IM3	IM4	IM5
Fish Lifts			X		
Groins	X				
Locate Potential Land Disturbing Activities away from Critical Areas		X			
Mulching	X	X			
Phase Construction		X			
Physical Barriers			X		
Preserve Onsite Vegetation		X			
Project Scheduling		X			
Retaining Walls		X			
Return Walls	X				
Revegetate		X			
Root Wad Revetments	X				X
Sediment Basin/Rock Dams		X			
Sediment Fences		X			
Sediment Traps		X			
Seeding		X			
Site Fingerprinting		X			
Sodding		X			
Soil Protection		X			
Surface Roughening		X			
Training ESC		X			
Transfer of Fish Runs			X		
Tree Revetments					X
Wildflower Cover		X			

Note: Clicking this link will access the 2007 document (*National Management Measures to Control Non-point Source Pollution from Hydromodification*). To find a specific practice, use the bookmarks.

3.2 Updated and Next Generation Practices

The practice sheets included in the section below are either updates to practices described in the 2007 guidance document or are next generation tools and techniques that have been identified as appropriate to address nonpoint source in the Chesapeake Bay watershed.

3.2.1 Advanced Hydroelectric Turbines

Description

Advanced hydroelectric turbines are the result of engineering studies of how the hydraulic components interact with biota and optimization of turbine operations designed to reduce effects on juvenile fish passing through the turbine as it operates.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☑ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Most research on advanced hydroelectric turbines has been conducted by electric power producers in the western United States. Improving the survival of juvenile fish by encouraging development of low impact turbines is also being pursued on a national scale by the U.S. Department of Energy and the U.S. Army Corps of Engineers. Research includes biological studies of turbine passage at field sites and hydraulic model investigations leading to innovative concepts for turbine design that will have environmental benefits and maintain efficient electrical generation.

Efficiency Data

Previous field studies have shown that improvements in the design of turbines have increased the survival of juvenile fish and researchers continue to examine the causes and extent of injuries from turbine systems, as well as the significance of indirect mortality and the effects of turbine passage on adult fish. Ongoing research is continuing to assess improvements in turbine design and operation as well as modeling to assess turbine-passage survival.

3.2.2 Bank Shaping and Planting

Description

Bank shaping and planting involves regrading a streambank to establish a stable slope angle, placing topsoil and other material needed for plant growth on the streambank, and selecting and installing appropriate plant species on the streambank.

- ☐ Protect Streambanks and Shorelines from Erosion
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- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Bank shaping and planting is most successful on streambanks where moderate erosion and channel migration are anticipated. Reinforcement at the toe of the bank is often required, particularly where flow velocities exceed the tolerance range for plantings and where erosion occurs below base flows.

Efficiency Data

Nearly 400 rock riprap grade-control structures (GCS) were recently placed in streams of western Iowa to reduce streambank erosion and protect bridge infrastructure and farmland. In that region, streams are characterized by channelized reaches, highly incised banks, and silt and sand substrates that normally support low macroinvertebrate abundance and diversity. Therefore, GCS composed of riprap provide the majority of coarse substrate habitat for benthic macroinvertebrates in these streams. Litvan et al. (2008) sampled 20 sites on Walnut Creek, Montgomery County, Iowa, to quantify macroinvertebrate assemblage characteristics (1) on GCS riprap, (2) at sites 5–50 meters (m) upstream of GCS, (3) at sites 5–50 m downstream of GCS and (4) at sites at least 1 kilometer (km) from any GCS (five sites each). Macroinvertebrate biomass, numerical densities and diversity were greatest at sites with coarse substrates, including GCS sites and one natural riffle site and relatively low at remaining sites with soft substrates. Densities of macroinvertebrates in the orders Ephemeroptera, Trichoptera, Diptera, Coleoptera and Acariformes were abundant on GCS riprap. Increases in macroinvertebrate biomass, density, and diversity at GCS might improve local efficiency of breakdown of organic matter and nutrient and energy flow, and provide enhanced food resources for aquatic vertebrates. However, lack of positive macroinvertebrate responses immediately upstream and downstream of GCS suggest that positive effects might be restricted to the small areas of streambed covered by GCS. Improved understanding of GCS effects at both local and ecosystem scales is essential for stream management when these structures are present.

3.2.3 Brush Mattressing

Description

A brush mattress is a layer (mattress) of interlaced live branches placed on a bank face, often with a live fascine and/or rock at the base. The mat is then secured to the bank by live and/or dead stakes and partially covered with fill soil to initiate growth of the cuttings.

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☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Brush mattressing is commonly used in Europe for streambank protection. It involves digging a slight depression on the bank and creating a mat or mattress from woven wire or single strands of wire and live, freshly cut branches from sprouting trees or shrubs. Branches approximately one inch in diameter are normally cut 6 to 9 feet long (the height of the bank to be covered) and laid in criss-cross layers with the butts in alternating directions to create a uniform mattress with few voids. The mattress is then covered with wire secured with wooden stakes 2.5 to 4 feet long. It is then covered with soil and watered repeatedly to fill voids with soil and facilitate sprouting; however, some branches should be left partially exposed on the surface. The structure might require protection from undercutting by placement of stones or burial of the lower edge. Brush mattresses are generally resistant to waves and currents and provide protection from the digging out of plants by animals. Disadvantages include possible burial with sediment in some situations and difficulty in making later plantings through the mattress.

Brush mattresses can restore riparian vegetation and habitat and enhance conditions for colonization of native plants. They reduce soil erosion and intercept sediment flowing down the streambank. After vegetation reaches a height of a few feet, it can improve fish habitat by shading the stream, lowering water temperatures and offering protection from predators (Allen and Fischenich 2000). Brush mattresses are also useful on steep, fast-flowing streams.

Cost Data

Costs for brush mattresses range between $3 and $14 per square foot (Allen and Fischenich 2000). Costs can be reduced by using free material from donation sites and volunteer labor. Costs related to project permitting or planning are not included in the estimate.

Design Guidance and Additional Information

Installation guidelines are available from the U.S. Department of Agriculture–Forest Service (USDA-FS) *Soil Bioengineering Guide* (USDA-FS 2002). Under the Ecosystem Management and Restoration Research Program (EMRRP), the U.S. Army Corps of Engineers has presented research on brush mattresses in a technical note (Brush Mattresses for Streambank Erosion Control).

3.2.4 Cross Vanes

Description

A rock cross vane is a stone structure consisting of footer and vane rocks constructed in a way that provides grade control and reduces bank erosion. The vane is composed of a center section perpendicular to the streambanks joined to two arms that extend into the streambank at the channel flow height. The rock cross vane accumulates sediment behind the vane arms, directs flow over the cross vane, and creates a scour pool downstream of the structure.

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Application and Purpose

Low-profile, in-stream structures, such as cross vanes, are primarily used to create aquatic habitat in the form of scour pools and for grade control on incising streams and rivers. Additionally, they are well-suited for channeling flow away from unstable banks. Cross vanes are typically suited for use in moderate- to high-gradient streams. When constructed and spaced properly, cross vanes can simulate the natural pattern of pools and riffles occurring in undisturbed streams while forming gravel deposits, which fish use as spawning grounds. Cross vanes can also be used to stabilize banks when designed properly. Cross vanes should be avoided in channels with bedrock beds or unstable bed substrates, and streams with naturally well-developed pool-riffle sequences.

Cross vanes are appropriate for the following:

- Stabilization of a vertically unstable stream bed requires grade control
- To direct erosional forces away from the streambanks and to the center of the channel
- When fish habitat enhancement and grade control are both desired
- For bridge protection. Cross vanes provide grade controls, prevent lateral migration of channels, increase sediment transport capacity and competence, and reduce footer scour
- To enhance or create recreational paddling opportunities
- Most suitable for rapid-dominated stream systems with gravel/cobble substrate

Cost Data

Construction costs for cross vanes are highly variable, depending on the design, size of the stone, availability of materials, and site constraints.

3.2.5 Establish and Protect Stream Buffers

Description

Stream buffers can provide cost-effective, long-term pollutant removal without having to construct and maintain structural controls. Specific stream buffer practices include establishing a stream buffer ordinance, developing vegetative and use strategies within management zones, establishing provisions for stream buffer crossings, integrating structural runoff management practices where appropriate, and developing stream buffer education and awareness programs.

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☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Establishing and protecting these areas is important to water quality protection. Land acquisition programs help to preserve areas considered critical to maintaining surface water quality. Stream buffers can also protect and maintain near-stream vegetation that attenuates the release of sediment into stream channels. Stream buffers should be protected and preserved as a conservation area because they provide many important functions and benefits, including the following:

- Providing a right-of-way for lateral movement
- Conveying floodwaters
- Protecting streambanks from erosion
- Treating runoff and reducing drainage problems from adjacent areas
- Providing nesting areas and other wildlife habitat functions
- Mitigating stream warming
- Protecting wetlands
- Providing recreational opportunities and aesthetic benefits
- Increasing adjacent property values

Efficiency Data

The biennial National Water Quality Inventory surveys shows no reduction in the percentage of degraded miles of streams since the early 1990s despite an exponential increase in river restoration projects to improve water quality, enhance in-stream habitat, and manage the riparian zone (Langendoen et al. 2009). This might suggest that many river restoration projects fail to achieve their objectives. This was found to be partly from a lack of understanding of the dynamics of the degraded riverine system and its interaction with the riparian zone. Vegetative riparian conservation measures are commonly used to stabilize failing streambanks. The shear strength of bank soils is greatly affected by the degree of saturation of the soils and root reinforcement provided by riparian vegetation. An integrated model was used to study the effectiveness of woody and herbaceous riparian buffers in controlling streambank erosion of an incised stream in northern Mississippi. Comparison of model results with observations showed that pore-water pressures are accurately predicted in the upper part of the streambank, away from the groundwater table. Simulated pore-water pressures deviate from those observed lower in the streambank near the phreatic surface. The discrepancies are mainly caused by differences in the simulated location of the phreatic surface and simulated evapotranspiration in case of the woody buffer. The modeling exercise further showed that a coarse rooting system, e.g., as provided by trees, significantly reduced bank erosion rates for this deeply incised stream.

The impact of different management of similar riparian land uses was studied in two pasture subreaches by Zaimes et al. (2008), who found that total streambank soil loss can be estimated by using magnitude of bank erosion, soil bulk density, and severely eroded bank area. Significant seasonal and yearly differences in magnitude of bank erosion and total soil loss were partially attributed to differences in precipitation and associated discharges. Riparian forest buffers had significantly lower magnitude of streambank erosion and total soil loss than the other two riparian land uses. Establishing riparian forest buffers along all the nonbuffered subreaches would have reduced streambank soil loss by an estimated 77 to 97 percent, significantly decreasing sediment in the stream. The pasture with cattle had consistently higher magnitudes of bank erosion than those for the pasture with horses for the entire study period. The pasture with cattle was also the only subreach to show an increase in eroding stream length (3 percent) and eroding area (10 percent) from 1998 to 2002. Riparian vegetation and land use are an integral part of streambank erosion, but high precipitation levels and associated high discharges can also influence the erosion process. Differences in the magnitude of bank erosion, severely eroded bank lengths and areas, and soil losses throughout this study are partially attributable to differences in precipitation that were associated with the occurrence of substantial discharge events. Other processes such as freeze and thaw events and season, which affected the density of the vegetation cover of the watershed were also implicated. The variation in soil losses from streambank erosion over the entire study period also suggest that a data set of many years is needed to get a good estimate of bank erosion contributions to stream sediment load. One-year data sets can be misleading in estimating the long-term contributions of bank erosion to stream sediment loads.

A partnership involving more than a dozen organizations, agencies, and businesses joined forces to construct a 800-foot *living shoreline* that rebuilt the barrier between the creek and the cove with natural materials, which was then planted with native plants to provide more stability (Blankenship 2009). The project relied on volunteers and multiple funders and was the first project in the Chesapeake Bay that involved the Corporate Wetland Restoration Partnership, which brings together government on environmental projects. That type of restoration project was envisioned in the draft habitat report that responded to President Barack Obama's Chesapeake Bay Executive Order of May of 2009. The report calls for using partnerships to build strategically placed "largescale, multifaceted restoration [projects] targeted at improving living resources."

Besides the living shoreline, curved rock structures were built at both ends of the cove to protect it from waves and to trap sand that will serve as beach habitat. The project included the construction of an oyster reef, which serves as habitat and buffers the shoreline from waves. Shallow water habitats, which had largely eroded away, were rebuilt and planted with marsh grasses. Reestablishing shallow water habitat, including oyster beds and mussel beds, will serve as foraging grounds for sea ducks, which should keep Hail Creek as one of the top five waterfowl habitats for years to come.

Langendoen et al. (2009) found that restoration projects could benefit from using proven models of stream and riparian processes to guide restoration design and to evaluate indicators of ecological integrity. The USDA has developed two such models: CONCEPTS and Riparian Ecosystem Management Model (REMM). Those models have been integrated to evaluate the impact of edge-of-field and riparian conservation measures on stream morphology and water quality. The physical process modules of the channel evolution model CONCEPTS and the riparian ecosystem model REMM have been integrated to create a comprehensive, stream-riparian corridor model that will be used to evaluate the effects of riparian buffer systems on in-stream environmental resources. The capability of REMM to dynamically simulate streambank hydrology and plant growth has been used to study the effectiveness of a deciduous tree stand and an eastern gamagrass buffer in controlling the stability of a streambank of an incised stream in northern Mississippi.

Cost Data

A study of cost-effectiveness analysis of vegetative filter strips and in-stream half-logs as tools for recovering scores on a fish index of biotic integrity (IBI) in the upper Wabash River in Indiana provided baseline data and a framework for planning and determining the cost of stream restoration (Frimpong et al. 2006). The authors found that costs per unit increase in IBI score with vegetative filter strips as the method of restoring stream health decreases with increasing stream order and decreasing recovery time. Another finding was that vegetative filter strips are likely a useful method, given cost considerations, for recovering lost IBI scores in an agricultural watershed. Three assumptions were made about recovery time for IBI scores (5, 15, and 30 years) and social discount rates (1, 3, and 5 percent), which were tested for sensitivity of the estimated cost-effectiveness ratios. The effectiveness of vegetative filter strips was estimated using fish IBIs and riparian forest cover from 49 first-order to fifth-order stream reaches. Half-log structures had been installed for approximately 2 years in the watershed before the study and provided a basis for estimates of cost and maintenance. Cost-effectiveness ratios for vegetated filter strips decreased from $387 to $277 per 100 meters for a 1 percent increase in IBI scores from first- to fifth-order streams with 3 percent discount and 30-year recovery. That cost, weighted by proportion of stream orders was $360 per 110 meters. On the basis of installation costs and an assumption of equal recovery rates, half-logs were two-thirds to one-half as cost-effective as vegetative filter strips. Half-logs would be a cost-effective supplement to filter strips in low-order streams if they can be proven to recover IBI scores faster than using filter strips alone.

Design Guidance and Additional Information

Maryland Department of the Environment Water Management Administration. 2000. *Maryland's Waterway Construction Guidelines* at http://www.mde.state.md.us/assets/document/wetlandswaterways/mgwc.pdf. Accessed February 2010.

3.2.6 Flow Augmentation

Description

- ☐ Protect Streambanks and Shorelines from Erosion
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Flow augmentation is the term used to describe operational procedures such as flow regulation, flood releases, or fluctuating flow releases that all have the potential for detrimental impacts on downstream aquatic and riparian habitat. Several options exist for creating minimum flows in the tailwaters below dams. Sluicing is the practice of releasing water through the sluice gate rather than through the turbines. For portions of the waterway immediately below the dam, the steady release of water by sluicing provides minimum flows with the least amount of water expenditure. Turbine pulsing is a practice involving the release of water through the turbines at regular intervals to improve minimum flows. In the absence of turbine pulsing, water is released from large hydropower dams only when the turbines are operating, which is typically when the demand for power is high.

Application and Purpose

The downstream effects that can be mitigated by using flow augmentation are highly variable because each impounded system is unique. The location of a dam within a river system, its age, depth and surface area, the hydraulic residence time, the regional climate, operation of the dam, and chemistry of the inflowing waters all influence how impoundments affect downstream water quality. Hydropower producers are faced with two environmental problems that can affect the water quality in areas downstream from dams (i.e., tailwaters). These are low concentrations of dissolved oxygen in the water released through the dam during generation and dry riverbeds that result when hydropower generation is shut off. Selecting any technique as the most cost-effective is site-specific and depends on several factors including adequate performance to achieve the desired in-stream and riparian habitat characteristic, compatibility with other requirements for operation of the hydropower facility, availability of materials, and cost.

Efficiency Data

Numerous studies have examined the effects of flow regulation on water quantity and quality by comparing an impounded system with an adjacent unimpounded system. Mitigation techniques to improve ecosystem health downstream of impoundments rely on the restoration of a more natural flow regime by creating and implementing site-specific, dam management plans.

A study by Ahearn et al. (2005) examined the effects of flow regulation on water quantity and quality by comparing an impounded system with an adjacent unimpounded system in California. The study showed that a strong seasonal cycle for total suspended solids (TSS), NO_3-N, TN, PO_4-P, TP, dissolved silicon, specific conductivity and flow into reservoirs in the lower Mokelumne River was attenuated by physical and chemical fluctuations creating a weak seasonal pattern. Dissolved silicon and TSS were the two constituents most efficiently sequestered by the reservoirs. While the reservoirs acted as traps for most constituents, NO_3-N and PO_4-P were produced during the drier years of the study, 2001 and 2002. In contrast, the unimpounded reference reach in the Cosumnes River was an annual source for all constituents measured. The Cosumnes delivers its highest NO_3-N concentrations during the winter months (December–April), while peak concentrations in the Mokelumne occur during the snowmelt (May–July) and baseflow (August–November) seasons. Because of downstream N limitation, the temporal shift in NO_3-N export might be contributing to accelerated algal growth in the reach immediately downstream and eventually to algal biomass loading to the downstream Sacramento–San Joaquin Delta.

In 2003 the Housatonic Valley Association (HVA) partnered with The Massachusetts Riverways Program (in the Department of Fish & Game) to begin measuring streamflow on several rivers below recreational reservoirs. The measurements indicated unnatural variations in streamflow at several sites that are detrimental to downstream aquatic life and habitat. A more *natural* flow regime is being reestablished in the streams to improve their ecological condition. The HVA has been meeting with Conservation Commissions, Lake Associations, and other stakeholders to develop guidelines for managing flows out of reservoirs. The goal is to improve ecosystem health downstream of impoundments by restoring a more natural flow regime by creating site-specific, dam management plans in the form of monthly flow recommendations using a methodology jointly developed by the U.S. Geological Survey (USGS) and the Massachusetts Department of Conservation and Recreation (DCR). The long-term goal is to develop guidance for Conservation Commissions throughout the commonwealth to help them craft Orders of Conditions for dam projects that include specific requirements to provide a year-round flow regime appropriate to the natural variability of the ecosystem downstream of the impoundment.

Cost Data

Since the early 1990s, the Tennessee Valley Authority (TVA) has spent about $60 million to address dissolved oxygen problems, including installing equipment to increase dissolved oxygen concentrations below 16 dams and operational changes and installing additional equipment to ensure minimum water flows through all its dams. TVA has since completed a second round of improvements by installing or enhancing oxygen systems at nine projects, and two new autoventing turbines have been installed at the Boone Dam. The additional oxygenation capacity will help offset the increased oxygen demands associated with delaying the seasonal drawdown of TVA reservoirs.

3.2.7 Joint Planting

Description

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Joint planting involves tamping live stakes of rootable plant material or rooted cuttings into soil in the interstices of porous revetments, riprap, or other retaining structures.

Joint planting is useful where rock riprap is required or already in place. It is successful 30 to 50 percent of the time, with first year irrigation improving survival rates. Live cuttings must have side branches removed and bark intact. They should range from 0.5 to 1.5 inches in diameter and be long enough to extend well into the soil, reaching into the dry season water level.

Application and Purpose

Joint planting can improve aquatic habitat by providing food and cover in the riparian zone and over the water when they are used in close proximity to the edge of the stream. Stone used at the base of the joint planting produces substrates suited for an array of aquatic organisms. Some of these organisms adapt to living on and within the rocks and some attach to the leaves and stems. The leaves and stems can also become food for shredders.

Species for joint planting systems can be selected to provide color, texture, and other attributes that add a pleasant, natural landscape appearance. Such plants for these systems include willow (*Salix* spp.), which tends to be the best from an adventitious rooting perspective and is normally an excellent choice. However other species such as poplar (*Populus* spp.), *Viburnum* spp., *Hibiscus* spp., shrub dogwood (*Cornus* spp.) and buttonbush (*Cephalanthus*) also work well. After establishment, joint planting system can reduce nonpoint pollution by intercepting sediment and attached pollutants that otherwise enter the stream from overbank flow areas.

Cost Data

Joint planting ranges in cost between $1 to $5 per square foot (Gray and Sotir 1996). Costs do not include riprap and assumes a spacing of four cuttings per square yard.

Design Guidance and Additional Information

Installation guidelines are available from the USDA-FS *Soil Bioengineering Guide* (USDA-FS 2002) and the USDA NRCS *Engineering Field Handbook*, Chapter 18 (USDA-NRCS 1992).

3.2.8 Legacy Effects of Dams and Dam Removal

Description

Dam removal is the process of dismantling and removing unsafe, unwanted or obsolete dams and restoring the original stream gradient to the extent possible.

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- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Dams serve a variety of important social and environmental purposes, including water supply, flood control, power generation, wildlife habitat, and recreation (USEPA 2007). Dam removal is undertaken either by owners of the dam or by public agencies and might become necessary for various reasons. Those include, most notably, the physical or structural deterioration of the dam resulting in a public safety risk, sediment accumulation in the impoundment/reservoir behind the dam and corresponding deleterious effects on the quality and quantity of water supplies. There are many things to consider when removing a dam, one of which is the function(s) of the dam and the status of that function (active versus inactive). Sometimes, the need for the dam is no longer as important as it once was, usually because of economic considerations. Finally, ecological concerns sometimes drive the need for dam removal. For example, migratory fish passage throughout United States rivers and streams is obstructed by more than 2 million dams and many other barriers such as blocked, collapsed, and perched culverts (USEPA 2007). Because dams are capital-intensive, long-term ventures, the opportunity for dam removal typically occurs infrequently, often corresponding to their periodic licensing renewal.

Efficiency Data

Many rivers and streams of the mid-Atlantic region have been altered by postcolonial floodplain sedimentation (legacy sediment) associated with numerous milldams. Several studies have shown the effect that colonization has had on the deposition of sediment into floodplains and estuaries (Jacobson and Coleman 1986; Hilgartner and Brush 2006). During the same time, many mill dams were installed, trapping the sediment behind them along with nutrients washed away from farm lands. Beavers played an important role in creating anabranching stream networks in the mid-Atlantic region during pre-settlement times, and beavers were an important factor in creating wetlands, performing a similar function to dams in sediment retention.

Little Conestoga Creek, Pennsylvania, a tributary to the Susquehanna River and the Chesapeake Bay, is one of those streams. Floodplain sedimentation rates, bank erosion rates, and channel morphology were measured annually during 2004–2007 at five sites along a 28-km length of Little Conestoga Creek with nine colonial era mill dams (one dam was still in place in 2007). A study by (Schenk and Hupp 2009) was part of a larger cooperative effort to quantify floodplain sedimentation, bank erosion, and channel morphology in a high sediment yielding region of the Chesapeake Bay watershed.

Data from the five sites were used to estimate the annual volume and mass of sediment stored on the floodplain and eroded from the banks for 14 segments along the 28-km length of creek. A bank and floodplain reach based sediment budget (sediment budget) was constructed for the 28 km by summing the net volume of sediment deposited and eroded from each segment. Mean floodplain sedimentation rates for Little Conestoga Creek were variable, with erosion at one upstream site (5 mm/year) to deposition at the other four sites (the highest was 11 mm/year) despite over a meter of floodplain aggradation from postcolonial sedimentation. Mean bank erosion rates range between 29 and 163 mm/year among the five sites. Bank height increased 1 m for every 10.6 m of channel width, from upstream to downstream ($R2 = 0.79$, $p < 0.0001$) resulting in progressively lowered hydraulic connectivity between the channel and the floodplain.

A knickpoint, approximately 9 km upstream of the dam, has produced a net erosional environment in the upstream two river segments. The floodplain experienced short periods of inundation nearly annually at the USGS stream gage, between the knickpoint and the dam, despite the heightened banks from postcolonial sedimentation and subsequent dam removals. Sediment trapping was recorded at four of the five study sites, indicating that the aggraded Little Conestoga Creek floodplain still functions as a sediment sink.

The study concluded that dam removals have many benefits, but they come with the cost of remobilizing large amounts of sediment. Managers and policy makers in the Northeast and mid-Atlantic states will have the additional burden of managing the storage and transport of legacy sediment. Dam removals in those regions can lead to large and sustained sediment pulses as legacy sediment is remobilized and transported further downstream, where increased sedimentation is a critical concern for imperiled estuarine resources, in this case, the Chesapeake Bay.

Gravel-bedded streams are thought to have a characteristic meandering form bordered by a self-formed, fine-grained floodplain. This ideal guides a multibillion-dollar stream restoration industry. Walter and Merritts (2008) mapped and dated many of the deposits along mid-Atlantic streams that formed the basis for this widely accepted model. Those data, as well as historical maps and records, show instead that before European settlement, the streams were small anabranching channels within extensive vegetated wetlands that accumulated little sediment but stored substantial organic carbon. Subsequently, 1 to 5 meters of slackwater sedimentation, behind tens of thousands of 17th- to 19th-century milldams, buried the presettlement wetlands with fine sediment. The findings show that most floodplains along mid-Atlantic streams are actually fill terraces, and historically incised channels are not natural archetypes for meandering streams. The study concludes that fluvial aggradation and degradation in the eastern United States were caused by human-induced base level changes from the following processes:

- Widespread milldam construction that inundated presettlement valleys and converted them into a series of linked slackwater ponds, coupled with deforestation and agricultural practices that increased sediment supply
- Sedimentation in ubiquitous millponds that gradually converted the ponds to sediment-filled reservoirs
- Subsequent dam breaching that resulted in channel incision through postsettlement alluvium and accelerated bank erosion by meandering streams
- The formation of an abandoned valleyflat terrace and a lower inset floodplain, which explains why so many eastern streams have bankfull (discharge) heights that are much lower than actual bank heights (note that assessments of bankfull discharge are crucial to estimates of flood potential and to design criteria for stream restoration)

A study by Skalak et al. (2009) demonstrated that the effects of dams on downstream channel morphology are minor. No significant differences in the water surface slope upstream and downstream of dams were observed. The study found that although monitoring studies of dam removals are becoming more common (Wildman and MacBroom 2005; Bushaw-Newton et al. 2002; Doyle et al. 2003; Chang 2008) empirical knowledge of the effects of dam removal is still limited, and most observations and conceptual models tend to focus on the transient effects of dam removal, the shorter-term patterns of upstream sediment mobilization, and downstream sediment storage.

Very little research has been conducted on the long-term effects of dam removal, although Graf (2006) suggests that one of the most important unanswered questions involves the likely course of channel change following dam removal. Skalak et al. suggest that the results of their study can provide some useful estimates of the long-term effects of dam removal on downstream channels because the reaches upstream of existing dams provide a useful surrogate for the channel downstream before dam construction. If the dam is removed, the following scenario is likely to occur. For an initial period of adjustment, sediment will be eroded from reservoir deposits upstream, and a transient sediment pulse will likely pass into and through the reach below the dam (Pizzuto 2002). During that period, changes in channel morphology and bed composition might be expected. However, after the new channel within the reservoir reach has stabilized, the supply of sediment and distribution of discharges should approach pre-dam levels, and the channel will slowly stabilize.

The issue of removing dams is highly controversial. Dams provide water quality benefits by removing sediment and nutrients (Harrison et al. 2009), a function historically performed by beaver dams and large woody debris (Valett et al. 2002). While providing water quality benefits, dams also hinder fish migration, limit sediment transport, and alter flow regimes. Because dams and their reservoirs persist for decades, river channels typically adjust to the altered hydrologic and sediment transport regimes that dams impose. Dam removal itself therefore represents a geomorphic disturbance to a quasi-adjusted riverine system. Removing a dam unleashes cascades of erosional and depositional processes that propagate both upstream and downstream, with the upstream response driving the downstream response.

The responses of aquatic ecosystems to elevated sediment loads and transformed channel morphology and hydrology are difficult to predict. Because dam presence and operation are known to be detrimental to preexisting aquatic ecosystems, dam removal is assumed to be beneficial, and emerging studies have supported ecological resiliency after removal (Stanley et al. 2002). Dam removal can also wreak havoc on already highly disturbed ecosystems. Further, the sediment released following a dam removal will inevitably be harmful to some downstream biota. The possibility exists that reservoirs can store high levels of contaminants, including heavy metals and other organic and inorganic compounds. Release of such materials after dam removal can create contaminant plumes with wide-ranging environmental consequences.

The benefits of removing dams include restoring flow fluctuations, allowing sediment transport, preventing temperature fluctuations, and allowing fish migration. When natural flow fluctuations are restored to a river, biodiversity and population densities of native aquatic organisms increase. Wetlands adjacent to rivers also benefit from dam removal. Riparian areas would likely flood more frequently, promoting riparian plant growth, revitalizing inland wetlands, and creating small, ephemeral ponds, which serve as nurseries for aquatic species. Dams can alter a river’s temperature by releasing water from the bottom of the impoundment where cooler water resides, so dam removal can restore a river’s natural water temperature range. Reproductive success, which often depends on appropriate timing for reaching spawning or breeding habits, can be improved by the removal of dams. Furthermore, dam removal decreases the risk of mortality for organisms that would otherwise have to pass through dams.

Cost Data

Costs of dam removal are site-specific and can vary from tens of thousands of dollars to hundreds of millions of dollars, depending on the size and location of the dam (USEPA 2007).

3.2.9 Live Crib Walls

Description

Live crib walls are hollow, box-like frameworks of untreated logs or timbers filled with riprap and alternating layers of suitable backfill and live branch layers and are used for slope, streambank, and shoreline protection.

☐ Protect Streambanks and Shorelines from Erosion

☐ Control Upland Sources of Sediment and Nutrients at Dams

☐ Restore In-stream and Riparian Habitat Function

☐ Reduce Pollutant Sources through Operational and Design Management

☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Live crib walls are constructed to protect the toes and banks of eroding stream reaches against scour and undermining, particularly at the outsides of meander bends where strong river currents are present. The log frameworks provide immediate protection from erosion while the live branch cuttings contribute long-term durability and ultimately replace the decaying logs. Additionally, live crib walls are effective in areas where encroachment into the stream channel should be avoided. When considering these structures as a stream restoration technique, the following limitations should be considered:

- Live crib walls should not be used where the channel bed is severely eroded or where undercutting is likely to occur (e.g., where the terrain is rocky or where narrow channels are bounded by high banks).
- Live crib walls are not intended to resist large lateral earth stresses, therefore their heights should be limited accordingly (as noted in the installation specifications).
- Live crib walls promote siltation and retain large amounts of bed material; therefore, they require continual monitoring for adverse streamflow patterns.

When choosing and preparing logs and woody cuttings for live crib walls, the following guidelines should be followed:

- Crib frameworks should be constructed from stripped logs or untreated lumber 4 to 6 inches (10 to 15 centimeters) in diameter.
- Live branches should be cut from fresh, green, healthy parent plants that are adapted to the site conditions whenever possible.
    1. Live branches should be 0.5 to 2.5 inches (1.3 to 6 centimeters) in diameter and should be long enough to reach the soil at the back of the wooden crib structure while projecting slightly from the crib face.

2. Commonly used woody plants for this measure include willow, poplar, and alder because they are versatile and have high growth rates with shrubby habits, fibrous root systems, and high transpiration rates especially when in leaf.
3. Live branch cuttings should be kept covered and moist at all times and should be placed in cold storage if more than a few hours elapse before installation.

- Fill soil should be native to the site, when possible, and should contain enough fine material to allow for the live branches to root and grow readily.

Cost Data

Live crib walls range in cost between $13 to $33 per square foot (Gray and Sotir 1996).

Design Guidance and Additional Information

Installation guidelines are available from the USDA-FS *Soil Bioengineering Guide* (USDA-FS 2002) and the USDA NRCS *Engineering Field Handbook*, Chapter 18 (USDA-NRCS 1992).

Additional Resources

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group. http://www.nrcs.usda.gov/technical/stream_restoration/PDFFILES/APPENDIX.pdf.

ISU (Iowa State University). 2006. *How to Control Streambank Erosion: Live Cribwall*. Iowa State University. http://www.ctre.iastate.edu/erosion/manuals/streambank/live_cribwall.pdf.

Mississippi State University, Center for Sustainable Design. 1999. *Water Related Best Management Practices in the Landscape: Live Cribwall*. Prepared for the U.S. Department of Agriculture, Natural Resource Conservation Service, Watershed Science Institute. http://www.abe.msstate.edu/csd/NRCS-BMPs/pdf/streams/bank/livecribwall.pdf.

Ohio DNR (Department of Natural Resources). 2007. *Ohio Stream Management Guide: Live Cribwalls*. Ohio Department of Natural Resources. http://www.ohiodnr.com/pubs/fs_st/streamfs/tabid/4178/Default.aspx.

3.2.10 Live Fascines

Description

Live fascines are a form of soil bioengineering that uses long bundles of live branch cuttings bound together in long rows and placed in shallow trenches following the contour on dry slopes and at an angle on wet slopes.

☐ Protect Streambanks and Shorelines from Erosion

☐ Control Upland Sources of Sediment and Nutrients at Dams

☐ Restore In-stream and Riparian Habitat Function

☐ Reduce Pollutant Sources through Operational and Design Management

☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Live fascines are suited to steep, rocky slopes, where digging is difficult (USDA-NRCS 1992). When cut from appropriate species (e.g., young willows or shrub dogwoods) that root easily and have long straight branches, and when properly installed, they immediately begin to stabilize slopes. Willow, alder, and dogwood cuttings are well suited for use in live fascines. Fascine bundles can range from 5 to 30 feet (1.5 to 9 m) in length, depending on handling and transportation limitations, with diameters ranging from 4 to 10 inches (10 to 25 cm). Untreated twine or wire used to tie the bundles should be at least 2 mm thick. If inert (dead) stakes are employed to secure the bundles, they should be made from 2 by 4 inch (5 by 10 cm) lumber cut on the diagonal with lengths of 2.5 feet (0.8 m) for cut slopes and 3 feet (0.9 m) for fill slopes. The goal is for natural recruitment to follow once slopes are secured. Live fascines should be placed in shallow contour trenches on dry slopes and at an angle on wet slopes to reduce erosion and shallow face sliding. Live fascines should be applied above ordinary high-water mark or bankfull level except on very small drainage area sites. In arid climates, they should be used between the high and low water marks on the bank. This system, installed by a trained crew, does not cause much site disturbance.

Establishing live fascines, also known as wattles, consists of the following:

- Preparing sausage-shaped bundles of live, woody plant cuttings
- Anchoring the bundles in shallow ditches in a slope or streambank with live or inert stout stakes, or both
- Partially burying the fascines to promote growth

As with other bioengineering measures, live fascines are an economical method when materials are locally available. Additionally, live fascines are often an effective measure when employed to

- Reduce runoff energy, and hence surface erosion, by braking a slope into a series of shorter slopes
- Protect other bioengineering measures from washout and undercutting
- Replace brush layers on suitable cut slopes (because they are easier to install)
- Protect streambanks from washout and seepage, particularly at toes where water levels fluctuate only moderately
- Stabilize or protect streambanks
- Provide habitat
- Reduce overland sediment loading

Cost Data

Live fascine costs range from $10 to $30 per foot for 6- to 8-inch bundles. Prices include securing devices for installation, twine (for fabrication), harvesting, transportation, handling, fabrication, and storage of the live-cut branch materials, excavation, backfill, and compaction. Costs vary with design, access, time of year, and labor rates.

Design Guidance and Additional Information

Installation guidelines are available from the USDA-FS *Soil Bioengineering Guide* (USDA-FS 2002) and the USDA NRCS *Engineering Field Handbook*, Chapter 18 (USDA-NRCS 1992). Under their Ecosystem Management and Restoration Research Program (EMRRP), the U.S. Army Corps of Engineers presents research on live fascines in a technical note (Live and Inert Fascine Streambank Erosion Control).

Additional Resources

Massachusetts DEP. 2006. *Massachusetts Nonpoint Source Pollution Management Manual: Live Fascines*. Massachusetts Department of Environmental Protection, Boston, MA. http://projects.geosyntec.com/NPSManual/Fact%20Sheets/Live%20Fascines.pdf.

Greene County Soil & Water Conservation District. No date. Construction Specification VS-01: Live Fascines. http://www.gcswcd.com/stream/library/pdfdocs/vs-01.pdf.

ISU (Iowa State University). 2006. *How to Control Streambank Erosion: Live Fascine*. Iowa State University. http://www.ctre.iastate.edu/erosion/manuals/streambank/live_fascine.pdf.

Mississippi State University, Center for Sustainable Design. 1999. *Water Related Best Management Practices in the Landscape: Live Fascine*. Prepared for the U.S. Department of Agriculture, Natural Resource Conservation Service, Watershed Science Institute. http://abe.msstate.edu/csd/NRCS-BMPs/pdf/streams/bank/livefacine.pdf.

Ohio DNR (Department of Natural Resources). 2007. *Ohio Stream Management Guide: Live Fascines*. Ohio Department of Natural Resources. http://www.ohiodnr.com/pubs/fs_st/streamfs/tabid/4178/Default.aspx.

3.2.11 Live Staking

Description

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Live staking is used to reestablish streambank vegetation and help stabilize selected slope areas. This form of soil bioengineering involves planting live cuttings from shrubs or trees along the streambank and is also known as woody cuttings, posts, poles, or stubs. Stakings provide long-term streambank stabilization with delayed initial onset and are best used as part of a system that includes immediate means of buffering banks from erosive flows (e.g., tree revetments, which can actually accrue sediments), a component to deter undercutting at the bed/bank interface (e.g., riprap or gabions) and a means of reducing the energy of incoming flows at their source.

Application and Purpose

Live staking is an economical method when local supplies of woody cuttings are readily available because implementing this measure requires minimal labor. When used effectively, live stakes can do the following:

- Act to trap soil particles in sediment laden water resulting from the erosion of adjacent land
- Slow water velocities, trap sediment, and control erosion when organized in clustered arrays along the sides of gullies
- Repair small earth slips and slumps that are frequently wet
- Help control shallow mass movement when placed in rows across slopes
- Promote bank stabilization

Live staking is a preventative measure and should be employed before severe erosion problems occur. Additionally, to be effective, live stakes should be

- Planted only on streams with low to moderate flow fluctuations
- Established in the original bank soil on moderate slopes of 4:1(h:v) or less
- Planted where appropriate lighting exists

- Used jointly with other restoration techniques especially on slopes with high erosion rates and incidents of mass wasting

When choosing and preparing woody material for live stakes, managers should follow these guidelines:

- Live stakes should be cut from fresh, green, healthy, dormant parent plants that are adapted to the site conditions whenever possible. Commonly used woody plants for this measure include willow, poplar, and alder because they are versatile and have high growth rates with shrubby habits, fibrous root systems, and high transpiration rates, especially when in leaf.
- Live stakes should have a diameter between 0.75 and 1.5 inches (2 to 4 cm) and should be long enough to reach below the groundwater table so that a strong root system can quickly develop. At least 1 foot (0.3 m) should be exposed to sunlight. Live woody posts with diameters up to 10 inches (0.25 m) and lengths ranging from 4 to 6 feet (1.2 to 1.8 m) can also be used at the discretion of the project manager.
- Live stakes should be kept covered and moist at all times and should be placed in cold storage if more than a few hours elapse between the cutting and replanting times.
- Vegetation selected should be able to withstand the degree of anticipated inundation, provide year round protection, have the capacity to become well established under sometimes adverse soil conditions, and have root, stem, and branch systems capable of resisting erosive flows.
- Specific site requirements and available cutting source will determine size.

Cost Data

The installed cost of live stakes typically ranges from $1 to $2 per stake, depending on local labor rates, proximity of harvesting area to site, and other site variables.

Design Guidance and Additional Information

Installation guidelines are available from the USDA-FS *Soil Bioengineering Guide* (USDA-FS 2002) and the USDA NRCS *Engineering Field Handbook*, Chapter 18 (USDA-NRCS 1992).

Additional Resources

ISU (Iowa State University). 2006. *How to Control Streambank Erosion: Live Stakes*. Iowa State University. http://www.ctre.iastate.edu/erosion/manuals/streambank/live_stakes.pdf.

Myers, R.D. 1993. *Slope Stabilization and Erosion Control Using Vegetation: A Manual of Practice for Coastal Property Owners. Live Staking*. Publication 93-30. Washington Department of Ecology, Shorelands and Coastal Zone Management Program, Olympia, WA. http://www.ecy.wa.gov/programs/sea/pubs/93-30/livestaking.html.

Walter, J., D. Hughes, and N.J. Moore. 2005. *Streambank Revegetation and Protection: A Guide for Alaska. Revegetation Techniques: Live Staking*. Revised Edition. Alaska Department of Fish and Game, Division of Sport Fish. http://www.sf.adfg.state.ak.us/SARR/restoration/techniques/livestake.cfm.

3.2.12 Log and Rock Check Dams

Description

Check dams are low structures built across a stream perpendicular to the flow. The most common use for check dams is to decrease the slope and velocity of a stream to control erosion.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The plunge pool below a check dam provides excellent fish habitat, and the downstream gravel bar often associated with the dam makes an excellent spawning bed. When used to enhance fish habitat, check dams should be placed far enough apart to ensure that the pool below a dam is above the backwater of the next dam downstream. That will reduce the possibility that the habitat pool of the upper dam can fill with deposits.

When constructed and spaced properly, check dams can simulate the natural pattern of pools and riffles occurring in undisturbed streams while forming gravel deposits that fish use as spawning grounds.

Check dams have also been used to prevent the movement of fine sediments into the mainstream channel, to aerate water, and to raise water levels past culvert invert elevations, thereby allowing fish passage.

Check dams should be avoided in the following areas:

- Channels with bedrock beds or unstable bed substrates
- Channels without well-developed, stable banks
- Streams with high bedload transport
- Streams with naturally well-developed pool-riffle sequences
- Reaches where the water temperature regime is negatively affected when the current is slowed

Cost Data

Check dams vary widely in cost depending on the design, availability and selection of materials, and site conditions.

Design Guidance and Additional Information

The following document provides design information and guidance for check dams.

Maryland Department of the Environment Water Management Administration. 2000. Maryland's Waterway Construction Guidelines. http://www.mde.state.md.us/assets/document/wetlandswaterways/mgwc.pdf.

3.2.13 Marsh Creation and Restoration

Description

Marsh creation and restoration is a useful vegetative technique that can address problems with erosion of shorelines. For shoreline sites that are highly sheltered from the effects of wind, waves, or boat wakes, the fill material is usually stabilized with small structures, similar to groins, which extend out into the water from the land. For shorelines with higher levels of wave energy, the newly planted marsh can be protected with an offshore installation of stone that is built either in a continuous configuration or in a series of breakwaters.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☑ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The exposed stems of marsh plants form a flexible mass that dissipates wave energy. As wave energy is diminished, the offshore transport and longshore transport of sediment are reduced. Ideally, dense stands of marsh vegetation can create a depositional environment, causing accretion of sediments along the intertidal zone rather than continued shore erosion. Marsh plants also form a dense mat of roots, which can add stability to the shoreline sediments. The basic approach for marsh creation is to plant a shoreline area in the vicinity of the tide line with appropriate marsh grass species.

Efficiency Data

Despite rapid growth in river restoration, few projects receive the necessary evaluation and reporting to determine their success or failure and to learn from experience. As part of the National River Restoration Science Synthesis, (Alexander and Allan 2006) interviewed 39 project contacts from a database of 1,345 restoration projects in Michigan, Wisconsin, and Ohio to (1) verify project information; (2) gather data on project design, implementation, and coordination; (3) assess the extent of monitoring; and (4) evaluate success and the factors that can influence it. Projects were selected randomly within the four most common project goals from a national database: in-stream habitat improvement, channel reconfiguration, riparian management, and water-quality improvement. About half of the projects were implemented as part of a watershed management plan and had some advisory group. Monitoring occurred in 79 percent of projects but often was minimal and seldom documented biological improvements. Baseline data for evaluation often relied on previous data obtained under regional monitoring programs using state protocols. Although 89 percent of project contacts reported success, only 11 percent of the projects were considered successful because of the response of a specific ecological indicator, and monitoring data were underused in project assessment. Estimates of ecological success, using three criteria from Palmer et al. (2005), indicated that half or fewer of the projects were ecologically successful, markedly below the success level that project contacts self-reported, and sent a strong signal of the need for well-designed evaluation programs that can document ecological enhancements.

3.2.14 Multi-Cell Culvert

Description

Roadway crossing, typically of smaller streams, where the main culvert at the stream channel is sized for bankfull discharge and additional culverts are placed on the floodplain to convey overbank flow up to the design discharge.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The use of a multi-cell culvert distributes stream conveyance during larger storm events across a larger portion of the stream/floodplain cross-section than the traditional single culvert system resulting in reduced flow velocities and better floodplain connectivity. In addition, the smaller primary culvert can increase flow depths during low flows enabling fish passage.

Multi-cell culverts typically consists of a primary culvert installed in line with the stream channel and sized with a cross-sectional area equivalent to the stream at bankfull discharge. One or more secondary culverts are at floodplain or bankful elevation at variable locations across the road crossing to provide passage of floodflow. Primary culvert inverts are often placed below the channel invert to allow water and sediments to pool within the culvert to enable fish passage. The placement and geometry of the primary culvert is intended to allow the natural transport of sediment in the stream channel and prevent scour of the streambed because of flow contraction (Rosgen 1996). The combined capacity of the primary and secondary culverts is the design flow.

Multi-cell culverts might not be appropriate for streams that are incised or actively incising, exhibit high-flow velocities, or streams that often carry a heavy debris load (Johnson and Brown 2000). Use of multi-cell culverts in such systems could result in perched culverts and debris jams. Rosgen (1996) type C or E channels might be most appropriate for use of multi-cell culverts (Maryland Waterways Construction Guidelines 2000).

Performance

Published data on the performance of multi-cell culverts is primarily limited to fish passage requirements and assessment of appropriate channels systems. Laboratory-scale model experiments investigating the scour and flow depth characteristics of multi-cell culverts showed reduction in overall scour pool volume and culvert perching of 52 percent and 55 percent, respectively (Wargo and Weisman 2006).

Design Guidance and Additional Information

Maryland Department of the Environment Water Management Administration. 2000. *Maryland's Waterway Construction Guidelines* at http://www.mde.state.md.us/assets/document/wetlandswaterways/mgwc.pdf. Accessed February 2010.

3.2.15 Natural Channel Design and Restoration

Description

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☑ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Natural stream channel design is based on fluvial geomorphology, which is the study of a stream's interactions with the local climate, geology, topography, vegetation, and land use—how a river carves its channel within its landscape. The underlying concept of natural stream channel design is to use a stable natural channel as a blueprint or template. Such a blueprint, or reference reach, will include the pattern, dimension, and profile for the stream to transport its watershed's flows and sediment as it dissipates energy through its geometry and in-stream structures. Project design (channel configuration, structures, nonstructural techniques, and the like) must account for the stream's ability to transport water and sediment.

Application and Purpose

Natural stream channel design depends on practioners accurately identifying stream classification types. Stream type is a powerful tool to use in decision making when combined with knowledge and field experience in natural stream channel design. In addition to providing a stable condition, natural stream channel design promotes a biologically diverse system. Many of the structures employed *buy time* until riparian vegetation becomes established and matures. Establishing a vegetated buffer that has long-term protection is key to natural design and provides a number of aquatic and terrestial benefits. Those benefits include root-mass that stabilizes the bank; shade that buffers stream temperature; leaves that provide energy, food, and shelter for wildlife; wildlife travel corridors; added roughness to the floodplain which helps to reduce stream energy; and the uptake of nutrients from the soil.

Many methods exist for classifying streams. One popular method for classification is Rosgen's Stream Classification System (Rosgen 1996). The purpose of that system is to classify streams on the basis of quantifiable field measurements to produce consistent, reproducible descriptions of stream types and conditions. Rosgen's classification hierarchy has four levels: geomorphic characterization (Level 1), morphological description (Level 2), stream condition assessment (Level 3), and validation and monitoring (Level 4).

Restoration of the proper dimension will ensure that the stream is connected to the floodplain so that riparian vegetation and other components that roughen the channel will mitigate damage from flood-flows. Structures used in natural stream channel design such as vanes, cross-vanes, and root-wads create and maintain pool habitat, which is often minimal in degraded channels. In other words, they maintain the dimension, pattern, and profile (or slope) of the stream. Restored streams provide for sediment transport and the sorting of bed material that results in the development of habitat diversity.

All successful natural stream channel designs achieve sediment transport, habitat enhancement, and bank and channel stabilization. The degree to which projects meet those goals depends on a project's specific objectives. Ultimately, a stream considered stable or *in equilibrium* can carry the sediment load supplied by the watershed without changing its dimension (cross-sectional area, width, depth, shape), pattern (sinuosity, meander pattern), or profile (longitudinal pattern and slope), and without aggrading (building up of bottom materials) or degrading (cutting down into the landscape and abandoning the natural floodplain).

Stream restoration is an increasingly popular management strategy for improving the physical and ecological conditions of degraded urban streams. In urban catchments, management activities as diverse as stormwater management, bank stabilization, channel reconfiguration and riparian replanting can be described as river restoration projects. Restoration in urban streams is both more expensive and more difficult than restoration in less densely populated catchments. High property values and finely subdivided land and dense human infrastructure (e.g., roads, sewer lines) limit the spatial extent of urban river restoration options, while stormwater and the associated sediment and pollutant loads can limit the potential for restoration projects to reverse degradation. To be effective, urban stream restoration efforts must be integrated within broader catchment management strategies. A key scientific and management challenge is to establish criteria for determining when the design options for urban river restoration are so constrained that a return toward reference or pre-urbanization conditions is not realistic or feasible and when river restoration presents a viable and effective strategy for improving the ecological condition of such degraded ecosystems.

Stream restoration should be performed to provide overall watershed improvement. One method for achieving that is the Stream Corridor Assessment survey developed by the Maryland Department of Natural Resources. The survey is a watershed management tool that identifies environmental problems and helps prioritize restoration opportunities on a watershed basis. Potential environmental problems commonly identified during the survey include stream channel alterations, excessive bank erosion, exposed pipes, inadequate stream buffers, fish migration blockages, trash dumping sites, near-stream construction, pipe outfalls, and unusual conditions. In addition, the survey records information on the location of potential wetlands creation sites and collects data on the general condition of in-stream and riparian habitats.

Efficiency Data

Restoration activities intended to improve the condition of streams and rivers are widespread throughout the country, but little information exists regarding types of activities and their effectiveness. Alexander and Allan (2006) developed a database of 1,345 stream restoration projects implemented from the years 1970 to 2004 for the states of Michigan, Ohio, and Wisconsin to analyze regional trends in goals, presence of monitoring, spatial distribution, size, and cost of river restoration projects. They found that data on individual projects were fragmented across multiple federal, state, and county agencies, as well as nonprofit groups and consulting firms. The most common restoration goals reported for the region were in-stream habitat improvement, bank stabilization, water-quality management, and dam removal. Hassett et al. (2005 and 2007) analyzed 4,700 stream restoration practices in the Chesapeake Bay watershed and Bernhardt et al. (2005) compiled a database for 37,099 projects in the National River Restoration Science Synthesis (NRRSS) database. Those studies found that the primary reasons for performing stream restoration are the following:

- Bank Stabilization
- Stormwater Management
- Flow Modification
- Channel Reconfiguration
- Fish Passage
- Riparian Management
- In-Stream Species Management
- Dam Removal/Retrofit
- Floodplain Reconnection
- In-Stream Habitat Improvement
- Aesthetics/Recreation/Education
- Water-Quality Management

The effects of upland disturbance and in-stream restoration on hydrodynamics and ammonium uptake in headwater streams was studied by Roberts et al. (2007) who found that the delivery of water, sediments, nutrients, and organic matter to stream ecosystems was strongly influenced by the catchment of the stream and can be altered greatly by upland soil and vegetation disturbance. Upland disturbance did not appear to influence stream hydrodynamics strongly, but it caused significant decreases in in-stream nutrient uptake. In October 2003, coarse woody debris (CWD) was added to one-half of the study streams (spanning the disturbance gradient) in an attempt to increase hydrodynamic and structural complexity, with the goals of enhancing biotic habitat and increasing nutrient uptake rates. CWD additions had positive short-term (within 1 month) effects on hydrodynamic complexity (water velocity decreased and transient storage zone cross-sectional area, relative size of the transient storage zone, fraction of the median travel time attributable to transient storage over a standardized length of 200 m, and the hydraulic retention factor increased) and nutrient uptake (NH_4^+ þ uptake rates increased). The results of this study suggest that water quality in streams with intense upland disturbances can be improved by enhancing in-stream biotic nutrient uptake capacity through measures such as restoring stream CWD.

Bukaveckas (2007) studied the interplay between hydrogeomorphic features and ecosystem processes within designed channels. Water velocity, transient storage, and nutrient uptake were measured in channelized (prerestoration) and naturalized (postrestoration) reaches of a 1-km segment of Wilson Creek (Kentucky) to assess the effects of restoration on mechanisms of nutrient retention. Stream restoration decreased flow velocity and reduced the downstream transport of nutrients. Median travel time was 50 percent greater in the restored channel because of lower reachscale water velocity and the longer length of the meandering channel. Transient storage and the influence of transient storage on travel time were largely unaffected except in segments where backwater areas were created. First order uptake rate coefficients for N and P were 30- and 3-fold higher (respectively) within the restored channel relative to its channelized state. Changes in uptake velocities were comparatively small, suggesting that restoration had little effect on biochemical demand. Results from this study suggest that channel naturalization enhances nutrient uptake by slowing water velocity.

Increased delivery of N because of urbanization and stream ecosystem degradation is contributing to eutrophication in coastal regions of the eastern United States according to Kaushal et al. (2008) who tested whether geomorphic restoration involving hydrologic *reconnection* of a stream to its floodplain could increase rates of denitrification at the riparian-zone–stream interface of an urban stream in Baltimore, Maryland. Rates of denitrification measured using in situ 15N tracer additions were spatially variable across sites and years and ranged from undetectable to 0.200 lg N (kg sediment). Concentrations of nitrate-N in groundwater and stream water in the restored reach were also significantly lower than in the unrestored reach, but that might have also been associated with differences in sources and hydrologic flow paths. Riparian areas with low, hydrologically connected streambanks designed to promote flooding and dissipation of erosive force for stormwater management had substantially higher rates of denitrification than restored high *nonconnected* banks and both unrestored low and high banks. Coupled measurements of hyporheic groundwater flow and in situ denitrification rates indicated that up to 1.16 mg NO_3-N could be removed per liter of groundwater flow through one cubic meter of sediment at the riparian-zone–stream interface over a mean residence time of

4.97 d in the unrestored reach, and estimates of mass removal of nitrate-N in the restored reach were also considerable. Mass removal of nitrate-N appeared to be strongly influenced by hydrologic residence time in unrestored and restored reaches. Results of the study suggest that stream restoration designed to reconnect stream channels with floodplains can increase denitrification rates, that there can be substantial variability in the efficacy of stream restoration designs, and that more work is necessary to elucidate which designs can be effective in conjunction with watershed strategies to reduce nitrate-N sources to streams.

Cost Data

The most common restoration activities found by Alexander and Allan (2006) were the use of sand traps and riprap, and other common activities were related to the improvement of fish habitat. The median cost was $12,957 for projects with cost data, and total expenditures since 1990 were estimated at $444 million. Over time, the cost of individual projects has increased, whereas the median size has decreased, suggesting that restoration resources are being spent on smaller, more localized, and more expensive projects. Only 11 percent of data records indicated that monitoring was performed, and more expensive projects were more likely to be monitored. Standardization of monitoring and record keeping and dissemination of findings are urgently needed to ensure that dollars are well spent and restoration effectiveness is maximized.

Design Guidance and Additional information

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3.2.16 Non-Eroding Roadways

Description

Non-eroding roadways refer to practices that reduce the sediment load to receiving waterbodies from dirt and gravel roads.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) has a chapter on the practice of Non-eroding Roadways. For additional information on the appropriate use and application of non-eroding roadways, see the 2007 guide.

In addition to the information contained in the 2007 guide, the following practices are recommended to reduce the sediment load from dirt and gravel roads.

Driving Surface Aggregate (DSA)

DSA is a specific gradation of crushed stone developed by the Center for Dirt and Gravel Road Studies specifically for use as a surface wearing course for unpaved roads. DSA achieves sediment reductions by decreasing erosion and transport of fine material from the road surface. Sandstone- and limestone-derived aggregates are preferred.

Raising the Road Profile

Raising the road profile involves importing material to raise the elevation of an unpaved road. It is typically practiced on roads that have become entrenched (lower than surrounding terrain). Raising the elevation of the road is designed to restore natural drainage patterns by eliminating the downslope ditch and providing cover for pipes to drain the upslope ditch. Removing the downslope ditch will eliminate concentrated flow conveyed in the ditch and create sheet flow. Raising the road profile achieves sediment reduction by controlling and reducing the volume of road runoff.

Raising the road profile involves importing fill material to raise the elevation of the roadway up to the elevation of the surrounding terrain. The road is filled to a sufficient depth as to eliminate the ditch on the downslope side of the road and encourage sheet flow. Shale and gravel are the most common fill materials for roads. Other potential recycled fill materials include ground glass, waste sand, automobile tires, clean concrete rubble, and the like.

Grade Breaks

Grade breaks are an intentional increase in road elevation on a downhill grade, which causes water to flow off of the road surface. It is designed to reduce erosion on the road surface by forcing water into the ditches or surrounding terrain. Erosion of the road surface is reduced by forcing runoff laterally off the road. In some cases, grade breaks are used to force water off the road entirely, serving as an additional drainage outlet. Sites where water is not forced off the road entirely convey the water into a roadside ditch.

Drainage Outlets

Drainage outlets are designed to capture water flowing in the roadside ditch and force it to leave the road area. There are two major types of drainage outlets. Turnouts (also called bleeders) or cutouts outlet water from the downslope road ditch. They usually consist of relatively simple cuts in the downslope road bank to funnel road drainage away from the road. Drainage that is carried by the upslope road ditch is usually outletted under the roadway by the use of a crosspipe (also called culvert, sluice pipe, or tile drain). Installing additional drainage outlets reduces concentrated flow, peak-flow discharges and sediment transport and delivery from unpaved roads and ditches into streams, and can increase infiltration. It does not affect sediment generation from the road surface or deliver in the upslope ditch; thus, all data on sediment reductions in this chapter are for a downslope ditch only, unless otherwise noted. Drainage outlets are to be placed in locations that have the least likelihood of reaching streams. If a newly added outlet conveys sediment to the stream, little, if any, sediment reductions will be obtained.

Berm Removal

A berm is a mound of earthern material that runs parallel to the road on the downslope side. Berms can be formed by maintenance practices and road erosion that lowers the road elevation over time. In many cases, the berm is unnecessary and creates a ditch on the downslope side of the road. The berm can be removed to encourage sheet flow into surrounding land instead of concentrated flow in an unnecessary ditch. Restoring sheet flow results in decreased runoff and sediment transport along the roadway, increase infiltration, and reduced maintenance associated with the road drainage system.

Effectiveness information for non-eroding roadway practices are summarized in Table 7-10.

Efficiency Data

Table 7-10. TSS reduction efficiencies estimated for each practice

Technique		TSS effectiveness estimate
Driving Surface Aggregate	Limestone*	50%
	Sandstone	55%
Raising the Road Profile		45%
Grade Breaks		30%
Additional Drainage Outlet		15%
Berm Removal		35%

Total nitrogen (TN) and total phosphorus (TP) removal is minimal with dirt and gravel road sediment control. One reason is that dirt and gravel roads are not fertilized. The other is that the environmental benefit association with dirt roads is such that N and P reductions are not anticipated, nutrient reductions are not a component of the average function of dirt and gravel roads. If N and P reductions are associated with dirt and gravel roads, sediment reductions should be tracked.

Design Guidance and Additional Information

For additional information on non-eroding roadways, see the following sources:

Controlling Nonpoint Source Runoff Pollution from Roads, Highways, and Bridges
http://www.epa.gov/owow/nps/roads.html

Erosion, Sediment, and Runoff Control for Roads and Highways
http://www.epa.gov/owow/nps/education/runoff.html

Gravel Roads: Maintenance and Design Manual—the purpose of the manual is to provide clear and helpful information for doing a better job of maintaining gravel roads. The manual is designed for the benefit of elected officials, mangers, and grader operators who are responsible for designing and maintaining gravel roads.
http://www.epa.gov/owow/nps/gravelroads

Low-Volume Roads Engineering Best Management Practices Field Guide
http://zietlow.com/manual/gk1/web.doc

Massachusetts Unpaved Roads BMP Manual
http://www.berkshireplanning.org/download/dirt_roads.pdf

Planning Considerations for Roads, Highways, and Bridges
http://www.epa.gov/owow/nps/education/planroad.html

Pollution Control Programs for Roads, Highways, and Bridges
http://www.epa.gov/owow/nps/education/control.html

Recommended Practices Manual: A Guideline for Maintenance and Service of Unpaved Roads
http://www.epa.gov/owow/nps/unpavedroads.html

The *Road Maintenance Video Set* is a five-part video series developed for the USDA-FS equipment operators that focuses on environmentally sensitive ways of maintaining low-volume roads. http://www.epa.gov/owow/nps/maint_videoset.html

3.2.17 Revetments

Description

Revetments are the stabilization of eroding streambanks and for shoreline protection by using designed structural measures, such as rock riprap, gabions, precast concrete wall units, and grid pavers.

☑ Protect Streambanks and Shorelines from Erosion

☐ Control Upland Sources of Sediment and Nutrients at Dams

☐ Restore In-stream and Riparian Habitat Function

☐ Reduce Pollutant Sources through Operational and Design Management

☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The purpose of revetments is to protect exposed or eroded streambanks from the erosive forces of flowing water. They are generally applicable where flow velocities exceed 6 feet per second or where vegetative streambank protection is inappropriate and necessary where excessive flows have created an erosive condition on a streambank.

Because each channel is unique, measures for structural streambank should be installed according to a design according to specific site conditions. Develop designs according to the following principles:

- Make protective measures compatible with other channel modifications planned or being carried out in the channel reaches.
- Use the design velocity of the peak discharge of the 10-year storm or bankfull discharge, whichever is less. Structural measures should be capable of withstanding greater flows without serious damage.
- Ensure that the channel bottom is stable or stabilized by structural means before installing any permanent bank protection.
- Streambank protection should begin at a stable location and end at a stable point along the bank.
- Changes in alignment should not be done without a complete analysis of effects on the rest of the stream system for both environmental and stability effects.
- Provisions should be made to maintain and improve fish and wildlife habitat. For example, restoring lost vegetation will provide valuable shade, food, and/or cover.
- Ensure that all requirements of state law and all permit requirements of local, state, and federal agencies are met.

Typical materials used for revetments are as follows:

Riprap. Riprap is the most commonly used material to structurally stabilize a streambank. While riprap will provide the structural stabilization necessary, the bank can be enhanced with vegetative material to slow the velocity of water, filter debris, and enhance habitat.

Gabions. Gabions are rectangular, stone-filled wire baskets. They are somewhat flexible in armoring channel bottoms and banks. They can withstand significantly higher velocities for the size stone they contain because of the basket structure. They also stack vertically to act as a retaining wall for constrained areas.

Reinforced Concrete. Reinforced concrete can be used to armor eroding sections of streambank by constructing walls, bulk heads, or bank linings. Provide positive drainage behind such structures to relieve uplift pressures.

Grid Pavers. Grid pavers are modular concrete units with or without void areas that can be used to stabilize streambanks. Units with void areas allow vegetation to establish. Such structures can be obtained in a variety of shapes, or they can be formed and poured in place. Maintain design and installation in accordance with manufacturer's instructions.

Modular Precast Units. Interlocking modular precast units of different sizes, shapes, heights, and depths have been developed for a wide variety of applications. The units serve in the same manner as gabions. They provide vertical support in tight areas as well as durability. Many types are available with textured surfaces. They also act as gravity retaining walls. They should be designed and installed in accordance with the manufacturers' recommendations. Openings in the units provide drainage and allow vegetation to grow through the blocks. Vegetation roots add strength to the bank.

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) provides various examples of types of revetments.

Design Guidance and Additional Information

Ohio DNR (Department of Natural Resources). 2007. *Ohio Stream Management Guide: Riprap Revetments*. Ohio Department of Natural Resources. http://www.ohiodnr.com/pubs/fs_st/streamfs/tabid/4178/Default.aspx.

3.2.18 Riparian Improvements

Description

Riparian improvements are strategies used to restore or maintain aquatic and riparian habitat around reservoir impoundments or along the waterways both upstream of and downstream from dams and include reducing sediment loading in the downstream watershed, improving riparian vegetation, eliminating barriers to fish migration, providing greater in-stream and riparian habitat diversity, and reducing flow-related effects on dams.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☑ Restore In-stream and Riparian Habitat Function
- ☑ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Maintaining and improving riparian areas upstream of and downstream from dams is an important consideration. Riparian improvements might be necessary along smaller-order streams if their ability to detain and absorb floodwater and stormwater has been impaired—often the result of removing forest cover or increasing watershed imperviousness. Cumulative effects on riparian areas of smaller streams include increased discharge volumes and velocities of water, which then result in more severe downstream flooding and increased storm damage or maintenance to existing structures, including dams. Information on techniques to mitigate effects on smaller streams is also in the Urban and Suburban chapter of this guidance (Chapter 3).

Design Guidance and Additional Information

The Iowa Department of Natural Resources (no date) recommends that the property owner or developer estimate the amount of time, materials, equipment, and labor necessary to complete the work as compared to those personally available. This is a subjective decision based on time, knowledge, and resource constraints.

- Construction activities should be conducted during periods of low flow.
- Construction equipment, activities, and materials should be kept out of the water to the maximum extent possible.
- All construction debris should be disposed of on land in such a manner that it cannot enter a waterway or wetland.

- Equipment for handling and conveying materials during construction should be operated to prevent dumping or spilling the material into waterbodies, streams, or wetlands.
- Care should be taken to prevent any petroleum products, chemicals, or other deleterious materials from entering waterbodies, streams, or wetlands.
- Clearing of vegetation, including trees in or immediately adjacent to waters of the state, should be limited to that which is absolutely necessary for construction of the project. All vegetative clearing material should be removed to an upland, non-wetland disposal site.

Each of the methods described in the manual requires observation and maintenance of the streambank erosion control practices over time. Observations should be made regularly before and after major stream flow events. Maintenance activities should include the following:

- Remove any debris that becomes entangled in the erosion control material and could damage the bank materials.
- Replace missing or damaged erosion control materials during times of low stream flow.
- Apply fertilizer to plant materials to enhance their growth each year.
- Apply fertilizer and weed control to buffer strip vegetation.
- Restrict livestock from steep banks and the areas containing the erosion control measures.

Riparian Buffers

Riparian buffers are described in Chapter 5 of this document.

3.2.19 Riprap

Description

Riprap is a layer of appropriately sized stones designed to protect and stabilize areas subject to erosion, slopes subject to seepage, or areas with poor soil structure.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) has a chapter on the practice of riprap. At the time of this writing, no additional information is provided pertaining to the practice. For information on the appropriate use and application for riprap, see the 2007 guide.

Cost Data

Riprap costs vary depending on the class of riprap, the location of the quarry, and installation practices. Prices typically range from $40 to $70 per ton.

3.2.20 Rock and Log Vanes

Description

Rock and log vanes are single-arm structures that are partially embedded in the streambed such that they are submerged even during low flows.

☐ Protect Streambanks and Shorelines from Erosion

☐ Control Upland Sources of Sediment and Nutrients at Dams

☐ Restore In-stream and Riparian Habitat Function

☐ Reduce Pollutant Sources through Operational and Design Management

☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Rock and log vanes induce secondary circulation of the flow, thereby promoting the development of scour pools. Vanes can also be paired and positioned in a channel reach to initiate meander development or migration. They essentially mimic the effect of a tree partially falling into the stream. They are usually placed along the streambank where erosion is occurring along the toe of the slope. The purpose of vanes is to reduce erosion along the streambank by redirecting the stream flow toward the center of the stream. In addition, they tend to create scour pools on the downstream side.

Vanes can be made of rock or log. They grade down from the bankfull elevation at the streambank to the channel invert at their terminus in the stream. Vanes generally extend out from the streambank one-third of the bankfull width and are angled upstream from the bank at a 20 to 30 degree angle. They should be carefully located and installed so as not to produce additional erosion on the upstream side where they meet the bank (eddy scour) or allow flows to outflank them, exacerbating existing bank erosion problems. The only difference between the log vane and the rock vane is the material used. The J-hook vane is basically the same as a rock vane with the exception that it curls around at the end in the shape of a “J.” The curved end portion serves to enhance downstream scour pool formation.

The following limitations apply to vanes:

- Vanes should not be used in unstable streams unless measures have been taken to promote stream stability so that it can retain a constant planform and dimension without signs of migration or incision.
- Vanes are ineffective in bedrock channels because minimal bed scouring occurs. Conversely, streams with fine sand, silt, or otherwise unstable substrate should be avoided because significant undercutting can destroy these measures.
- Vanes should not be used in stream reaches that exceed a 3 percent gradient.

- Vanes should not be used in streams with large sediment or debris loads.
- Banks opposite the structures should be monitored for excessive erosion.

Cost Data

Rock and log vanes vary greatly in cost depending on the design, availability and selection of materials, and site conditions.

Design Guidance and Additional Information

The following documents provide design information and guidance for vanes.

Stream Restoration: A Natural Channel Design Handbook, prepared by the North Carolina Stream Restoration Institute and North Carolina Sea Grant. http://www.bae.ncsu.edu/programs/extension/wqg/srp/sr_guidebook.pdf

The Virginia Stream Restoration & Stabilization Best Management Practices Guide. Department of Conservation and Recreation, Division of Soil and Water Conservation. 2004. http://www.dcr.virginia.gov/soil_and_water/documents/streamguide.pdf

3.2.21 Selective Withdrawal

Description

Selective withdrawal describes the use of intake structures on reservoirs that are capable of releasing waters from specific locations within a stratified water column to address downstream water quality objectives.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☑ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Selective withdrawal in reservoir releases depends on the volume of water storage in the reservoir, the timing of the release relative to storage time, and the level from which the water is withdrawn. Selective withdrawal takes advantage of the phenomenon of reservoir stratification, in which the water column exhibits various quality characteristics respective to water depth. Multilevel intake devices in storage reservoirs allow selective withdrawal of water according to temperature, dissolved oxygen levels or other stratified water quality characteristics. They can be particularly useful in stratified reservoirs so that they can be operated to meet downstream water quality objectives such as to maintain downstream temperature conditions or minimize the turbidity of discharge waters. While most selective withdrawal intake structures are built during initial reservoir construction, release structures can be successfully modified to incorporate selective withdrawal as a retrofit, although doing so could be costly.

3.2.22 Shoreline Sensitivity Assessment

Description

Shoreline sensitivity assessments are methodologies that apply to shoreline areas and are used to evaluate, classify, and assess stability and erosion vulnerabilities in various types of lakes, reservoirs, estuaries, and coasts.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☑ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Langendoen et al. (2009) found that restoration projects could benefit from using proven models of stream and riparian processes to guide restoration design and to evaluate indicators of ecological integrity. The USDA has developed two such models: the channel evolution computer model (CONCEPTS) and REMM.

Efficiency Data

The physical process modules of the channel evolution model CONCEPTS and the riparian ecosystem model REMM have been integrated to create a comprehensive stream-riparian corridor model that can be used to evaluate the effects of riparian buffer systems on in-stream environmental resources (Langendoen et al. 2009). The models have been integrated to evaluate the impact of edge-of-field and riparian conservation measures on stream morphology and water quality. The capability of REMM to dynamically simulate streambank hydrology and plant growth has been used to study the effectiveness of a deciduous tree stand and an eastern gamagrass buffer in controlling the stability of a streambank of an incised stream in northern Mississippi.

3.2.23 Step Pools

Description

Step pools are rock grade-control structures constructed in the stream channel that recreate natural step-pool channel morphology.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Step-pool channels are characterized by a succession of channel-spanning steps formed by large, grouped boulders called clasts that separate pools containing finer bed sediments. They are constructed in higher gradient channels where a fixed-bed elevation is required. Step pools are built in series and allow for *stepping down* the channel over a series of drops. The steps are constructed of large rock with the pools containing smaller rock material. As flow tumbles over the step, energy is dissipated into the plunge pool.

Step-pools can be used to backwater a culvert, providing improved fish passage and can be used to connect two reaches with different elevations.

Step-pool morphologies are typically associated with well-confined, high-gradient channels with slopes greater than 3 percent, having small width-depth ratios and bed material dominated by cobbles and boulders. Step pools generally function as grade-control structures and aquatic habitat features by reducing channel gradients and promoting flow diversity. At slopes greater than roughly 6.5 percent, similar morphologic units termed cascades spanning only a portion of the channel width are formed in these channel conditions.

Step pools are not generally considered a habitat enhancement practice. The enhancement potential is in the form of maintaining fish passage and expanding the total amount of habitat available for fish.

Cost Data

Construction costs for step pools are highly variable, depending on the design, size of the stone, availability of materials, and site constraints.

Design Guidance and Additional Information

The following documents provide design information and guidance for vanes.

Stream Restoration: A Natural Channel Design Handbook, prepared by the North Carolina Stream Restoration Institute and North Carolina Sea Grant.
http://www.bae.ncsu.edu/programs/extension/wqg/srp/sr_guidebook.pdf

The Virginia Stream Restoration & Stabilization Best Management Practices Guide, Department of Conservation and Recreation, Division of Soil and Water Conservation 2004.
http://www.dcr.virginia.gov/soil_and_water/documents/streamguide.pdf

3.2.24 Streambank Dewatering

Description

Streambank dewatering is the practice of using groundwater level management adjacent to an eroding streambank to lower static water pressure on bank and reduce erosion potential.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Streambank dewatering is the practice of actively or passively reducing the static water level immediately adjacent to a streambank with erosion potential for the purposes of reducing pore water pressure within the streambank. The reduced pore pressure improves the shear strength of bank soils. Because shear strength is one of several governing factors for bank failure, a reduction in bank failure rates and potential is expected.

Dewatering systems can take several forms. Specific designs that are discussed in the research literature are vertical groundwater wells managed by an active pumping system and installing horizontal tile drains, which provide passive drainage for the riparian zone. While other dewatering system designs might be possible, no published information on additional methods are available. The location, depth, capacity, and configuration of the dewatering systems vary depending on local conditions, and no published guidance on streambank dewatering is available.

Using streambank dewatering is not widespread. A number of alternative practices are available that might be more suitable for a particular application. Dewatering systems that rely on pumping systems have an inherent long-term maintenance and operational cost. For those reasons, streambank dewatering might be most appropriate for short-term use or in areas where grading and practice installation along the bank are not possible (such as because of utility conflicts, access constraints, and the like). In addition, it is important to note that streambank dewatering can affect riparian habitat condition and available groundwater for riparian habitat. Where wetlands are present adjacent to the stream, dewatering could affect the wetland condition.

Performance

Shields et al. (2009) reported that streambank dewatering resulted in reduced rates of bank erosion on a deeply incised channel in northern Mississippi. Pumped and passive drain systems exhibited bank erosion of 0.21 m and 0.23 m, respectively, over a 2-year period of two wet seasons, while a streambank without dewatering exhibited erosion of 0.43 m. While reduced bank erosion was observed where streambank dewatering was used, the researchers note that at some individual monitoring stations, bank erosion exceeded control values.

Cost Effectiveness

While no published cost information is available, Shields et al. (2009) report that initial costs of dewatering systems was significantly lower than more orthodox bank stabilization measures, while it was acknowledged that long-term pumping and maintenance costs were neglected.

3.2.25 Toe Protection

Description

Toe protection refers to the installation of erosion resistant material, typically stone, near and at the water line along shorelines and streams to reduce wave reflection and scour of the land water interface.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The purpose of toe protection is to dissipate wave and scour energy at the land water interface and therefore reduce shoreline and streambank erosion.

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) provides information on the use of toe protection to reduce shoreline erosion. While the installation techniques and methods differ slightly where toe protection is used to reduce streambank erosion, the practice is principally the same.

Efficiency Data

Efficiency data on toe protection in streambanks is limited. However, recent research projects have shown reduced loss of streambank where toe protection is implemented on eroding channels. A modeling study in the Lake Tahoe basin using the Bank-Stability and Toe-Erosion Model (BSTEM) predicted that the application of a 1.0-m-high rock toe protection would reduce bank erosion by 69–100 percent (Simon et al. 2009). It was further noted that only 14 percent of the sediment loss in the streambank of the studied reach was from the toe region, the remaining sediment loss resulted from mass wasting of the overlying streambank indicating the importance of the land water interface in overall stream sediment dynamics.

3.2.26 Turbine Operation

Description

Turbine operations include implementing changes in the turbine start-up procedures that can enlarge the zone of withdrawal to include more of the epilimnetic waters in the downstream releases.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☑ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

In an improvement effort that included changes in turbine operation, the TVA made operational changes and installed additional equipment to ensure that minimum water flows through its dams.

Cost Data

Since the early 1990s, the TVA has spent about $60 million to address dissolved oxygen problems below dams, including turbine operation.

Reference

Tennessee Valley Authority. No date. *Tailwater Improvements: Improving Water Quality Below TVA Hydropower Dams*.

3.2.27 Turbine Venting

Description

Turbine venting is the practice of injecting air into water as it passes through a turbine. If vents are inside the turbine chamber, the turbine will aspirate air from the atmosphere and mix it with water passing through the turbine as part of its normal operation. Autoventing turbines are constructed with hub baffles or deflector plates placed on the turbine hub upstream of the vent holes to enhance the low-pressure zone in the vicinity of the vent and thereby increase the amount of air aspirated through the venting system.

☐ Protect Streambanks and Shorelines from Erosion
☐ Control Upland Sources of Sediment and Nutrients at Dams
☐ Restore In-stream and Riparian Habitat Function
☑ Reduce Pollutant Sources through Operational and Design Management
☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Developments in turbine venting technology show potential for aspirating air with no resulting decrease in turbine efficiency. However, applying turbine venting technologies is site-specific, and outcomes will vary considerably.

Efficiency Data

Turbine efficiency relates to the amount of energy output from a turbine per unit of water passing through the turbine. Efficiency decreases as less power is produced for the same volume of water. In systems where the water is aerated before passing through the turbine, part of the water volume is displaced by the air, thus leading to decreased efficiency.

3.2.28 Vegetated Buffers

Description

Vegetated buffers are naturally occurring, composed of vegetative areas that provide physical separation between a waterbody and adjacent land uses.

Application and Purpose

Vegetated buffers remove nutrients and other pollutants from runoff, trap sediments, and shade the waterbody to optimize light and temperature conditions for aquatic plants and animals.

☐ Protect Streambanks and Shorelines from Erosion
☐ Control Upland Sources of Sediment and Nutrients at Dams
☑ Restore In-stream and Riparian Habitat Function
☐ Reduce Pollutant Sources through Operational and Design Management
☐ Restore Stream and Shoreline Physical Characteristics

Efficiency Data

Protecting or restoring modest-sized patches of living shoreline can provide adequate prime waterfowl habitat (Blankenship 2009). Hail Creek, a tiny waterway at the tip of a peninsula that is separated by a narrow swath of land from the Chester River, is shorter than a half-mile long. But, despite its diminutive size, the creek and its surrounding marshes, part of the Eastern Neck National Wildlife Refuge, are one of the top five waterfowl habitats in Maryland, with large concentrations of bufflehead and scaup, as well as black ducks, Canada geese, and other species. The creek has about 100 acres of underwater grasses, in contrast with nearby areas where grasses have been declining. Those habitats have faced increasing danger in recent years from rising water levels that have been eating away at a narrow barrier of land that separates the upstream end of the creek from Hail Cove along the Chester River. If breached, the sheltered creek habitats and adjoining wetlands would suddenly be subjected to highly erosive waves.

Besides the living shoreline, curved rock structures were built at both ends of the cove to protect it from waves and to trap sand that serves as beach habitat. The project included constructing an oyster reef, which serves as habitat and buffers the shoreline from waves. Shallow water habitats, which had largely eroded away, were rebuilt and planted with marsh grasses. Reestablishing shallow water habitat, including oyster beds and mussel beds, will serve as foraging grounds for sea ducks, which should keep Hail Creek as one of the top five waterfowl habitats for years to come.

Cost Data

A partnership involving more than a dozen organizations, agencies, and businesses joined forces to construct an 800-foot *living shoreline*. They rebuilt the barrier between the creek and the cove with natural materials, which was then planted with native plants to provide more stability. The project relied on volunteers and multiple funders and was the first project in the Chesapeake that involved the Corporate Wetland Restoration Partnership, which brings together government on environmental projects. This type of restoration project was envisioned in the draft habitat report that responded to President Barack Obama's Executive Order of May 2009 that calls for using partnerships to build strategically placed "largescale, multifaceted restoration [projects] targeted at improving living resources."

3.2.29 Vegetated Filter Strips

Description

Vegetated filter strips are low-gradient vegetated areas that filter overland sheet flow. Runoff must be evenly distributed across the filter strip, and channelized flows decrease their effectiveness.

- ☐ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☑ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☐ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Vegetated filter strips should have relatively low slopes and adequate length to provide optimal sediment control and should be planted with erosion-resistant plant species. The main factors that influence the removal efficiency are the vegetation type, soil infiltration rate, and flow depth and travel time. Such factors are dependent on the contributing drainage area, slope of strip, degree and type of vegetative cover, and strip length. Maintenance requirements for vegetated filter strips include sediment removal and inspections to ensure that dense, vigorous vegetation is established, and concentrated flows do not occur.

Efficiency Data

A study of cost-effectiveness analysis of vegetative filter strips and in-stream half-logs as tools for recovering scores on a fish IBI in the upper Wabash River in Indiana provided baseline data and a framework for planning and determining the cost of stream restoration (Frimpong et al. 2006). Three assumptions were made about recovery time for IBI scores (5, 15, and 30 years) and social discount rates (1, 3, and 5 percent), which were tested for sensitivity of the estimated cost-effectiveness ratios. The effectiveness of vegetative filter strips was estimated using fish IBIs and riparian forest cover from 49 first-order to fifth-order stream reaches. Half-log structures had been installed for approximately 2 years in the watershed before the study and provided a basis for estimates of cost and maintenance.

Cost Data

Frimpong et al. (2006) found that costs per unit increase in IBI score with vegetative filter strips as the method of restoring stream health decreases with increasing stream order and decreasing recovery time. Another finding of this study was that vegetative filter strips is likely a useful method, given cost considerations, for recovering lost IBI scores in an agricultural watershed. Cost-effectiveness ratios for vegetated filter strips decreased from $387 to $277 per 100 meters for a 1 percent increase in IBI scores from first- to fifth-order streams with 3 percent discount and 30-year recovery. That cost, weighted by proportion of stream orders was $360 per 110 meters. On the basis of installation costs and an assumption of equal recovery rates, half-logs were two-thirds to one-half as cost-effective as vegetative filter strips. Half-logs would be a cost-effective supplement to filter strips in low-order streams if they can be proven to recover IBI scores faster than using filter strips alone.

3.2.30 Vegetated Gabions

Description

A gabion is a rectangular basket made of heavily galvanized wire mesh filled with small-to medium-sized rock. The gabions are laced together and installed at the base of a bank to form a structural toe or sidewall. Vegetation can be incorporated by placing live branches between each layer of rock-filled baskets. The branches take root inside the gabions and in the soil behind the structures. Their roots eventually consolidate the structure and bind it to the slope.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) contains a chapter on the practice of vegetated gabions. At the time of this writing, no additional information is provided pertaining to this practice. For information on the appropriate use and application for vegetated gabions, see the 2007 guide.

Cost Effectiveness

Vegetated gabions are comparable to vegetated geogrids and vegetated reinforced soil slope, ranging from $15 to $40 per square foot. Construction costs vary with the structure's design (materials, depth into the streambed, height and width, and such), site access, time of year, degree and type of associated channel redefinition, and equipment and labor rates.

3.2.31 Vegetated Geogrids

Description

Vegetated geogrids are the covering of soil with erosion control fabric (geotextile) on the slope of the bank. The erosion control fabric is secured by tucking it into the slope. Live cuttings are placed between the geogrids, and a root structure is established to bind the soil within and behind the geogrids. The toe of the bank is stabilized by layers of rock on top of the same geotextile fabric.

- ☑ Protect Streambanks and Shorelines from Erosion
- ☐ Control Upland Sources of Sediment and Nutrients at Dams
- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) has a chapter on the practice of vegetated geogrids. At the time of this writing, no additional information is provided pertaining to this practice. For information on the appropriate use and application for vegetated geogrids, see the 2007 guide.

Cost Data

Vegetated geogrids range in cost from $20 to $40 per square foot depending on the design and construction techniques (Sotir and Fischenich 2003).

3.2.32 Vegetated Reinforced Soil Slope (VRSS)

Description

The vegetated reinforced soil slope (VRSS) soil system is an earthen structure constructed from living, rootable, live-cut, woody plant material branches, bare root, tubling or container plant stock, along with rock, geosynthetics, geogrids, and/or geocomposites.

- ☑ Protect Streambanks and Shorelines from Erosion
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- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

The *National Management Measures to Control Nonpoint Sources Pollution from Hydromodification* document (USEPA 2007) has a chapter on the practice of vegetated reinforced soil slopes. At the time of this writing, no additional information is provided pertaining to this practice. For information on the appropriate use and application for vegetated reinforced soil slopes, see the 2007 guide.

Cost Data

Vegetated reinforced soil slopes structure costs typically range from $15 to $35 per square face foot. These prices do not include design, which can be extensive because of the required geotechnical data collection and analysis. Harvesting, transportation, handling, and storage of the live-cut branch materials or rooted plants can significantly influence cost and are included in the above range.

Construction costs also vary with the structure’s design (materials, depth into the streambed, height and width, and such), site access, time of year, degree and type of associated channel redefinition, and equipment and labor rates. Installation is relatively complex because it can require large earth-moving machinery. Installation, excavation, and soil replacement costs are usually high.

3.2.33 Weirs

Description

Using weirs is a technique in which boulders or logs are laced across the channel and anchored to the channel bank or bed (or both) to check the water and raise its level for diversion purposes; they are designed to allow overtopping.

- ☐ Protect Streambanks and Shorelines from Erosion
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- ☐ Restore In-stream and Riparian Habitat Function
- ☐ Reduce Pollutant Sources through Operational and Design Management
- ☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Low-profile, in-stream structures such as vortex rock weirs and W-weirs are primarily used to create aquatic habitat in the form of scour pools and for grade control on incising streams and rivers. Additionally, they are well-suited for channeling flow away from unstable banks. Weirs are used to collect and retain gravel for spawning habitat, to deepen existing resting/jumping pools; to create new pools above or below the structure, to trap sediment, to aerate the water, and to promote deposition of organic debris.

There are several types of weirs, but the two most common types for stream restoration are the W-weir and the rock vortex weir. Both types provide grade control and reduce bank erosion. The weirs accumulate sediment behind the weir arms and create a scour pool downstream of the structure. A rock W-weir is a stone structure composed of footer and vane rocks and consists of four weir arms arranged in a *W* fashion across the channel. A rock vortex weir consists of footer and vane rocks, and the form of the rock vortex weir is parabolic and spans the channel width. The rock vortex weir accumulates sediment behind the weir arms and creates a scour pool downstream of the structure.

Weirs are typically suited for use in moderate to high gradient streams. W-weirs are best used in rivers with bankfull widths greater than 40 feet (12 meters). Weirs should be avoided in channels with bedrock beds or unstable bed substrates, and streams with naturally well-developed, pool-riffle sequences.

Cost Data

Construction costs for weirs are highly variable, depending on width of the channel, size of the stone, availability of materials, and site constraints.

Design Guidance and Additional Information

The following document provides design information and guidance for vanes.

Stream Restoration: A Natural Channel Design Handbook, prepared by the North Carolina Stream Restoration Institute and North Carolina Sea Grant. http://www.bae.ncsu.edu/programs/extension/wqg/srp/sr_guidebook.pdf

3.2.34 Wing Deflectors

Description

Wing deflectors are devices made of a variety of materials that project outward into the channel from one or both streambanks but do not extend entirely across the channel. Wing deflectors are especially effective in wide, shallow, low-gradient streams to create pools and cover.

☐ Protect Streambanks and Shorelines from Erosion
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☑ Restore Stream and Shoreline Physical Characteristics

Application and Purpose

Wing deflectors are designed to deflect flows away from the bank and create scour pools by constricting the channel and accelerating flow. The structures can be installed in series on alternate streambanks to produce a meandering thalweg and stream diversity. The most common design is a rock and rock-filled log crib deflector structure. The design bases the size of the structure on anticipated scour. These structures need to be installed far enough downstream from riffle areas to avoid backwater effects that could drown out or damage the riffle. This design should be employed in streams with low physical habitat diversity, particularly channels that lack pool habitats. Construction on a sand bed stream can be susceptible to failure and should be constructed with the use a filter layer or geotextile fabric beneath the wing deflector structure (FISRWG 1998).

When two wing deflectors are placed opposite each other, they serve to narrow or constrict the flow of water. The double wing deflector is more often used in urban applications because it forces the water toward the center of the channel and deepens the baseflow channel. Double wing deflectors also create an area of increased velocity between them, enhancing riffle habitat between and just upstream of the structure. This increased velocity also creates an area of scour, creating pool habitat downstream of the structure. The construction is the same as a single wing deflector except that in some instances, a rock sill at the stream invert can connect the two structures.

Both single and double wing deflectors have significant habitat enhancement potential. These structures enhance habitat through pool formation, the narrowing and deepening of the baseflow channel, and the enhancement of riffle habitat. Deflectors protect the bank in the immediate area and provide desirable changes to the stream flow patterns. They are relatively easy to construct, inexpensive, easily modified to suit on-site conditions, and are adaptable for use with other treatments. They are significantly cheaper to install than dam-type structures. They are effective in sections of streams where the banks are too low or too wide for dams.

The following limitations apply to stream deflectors:

- Deflectors should not be used in unstable streams that do not retain a constant planform or are actively incising at a moderate to high rate.
- Deflectors are ineffective in bedrock channels because minimal bed scouring occurs. Conversely, streams with fine sand, silt, or otherwise unstable substrate should be avoided because significant undercutting can destroy the measures.
- Deflectors should not be used in stream reaches that exceed a 3 percent gradient.
- Deflectors should not be used in streams with large sediment or debris loads.
- Banks opposite these structures should be monitored for excessive erosion.

Design Guidance and Additional Information

Additional Resources

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group. http://www.nrcs.usda.gov/technical/stream_restoration/PDFFILES/APPENDIX.pdf.

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