National Management Measures to Control Nonpoint Source Pollution from Hydromodification

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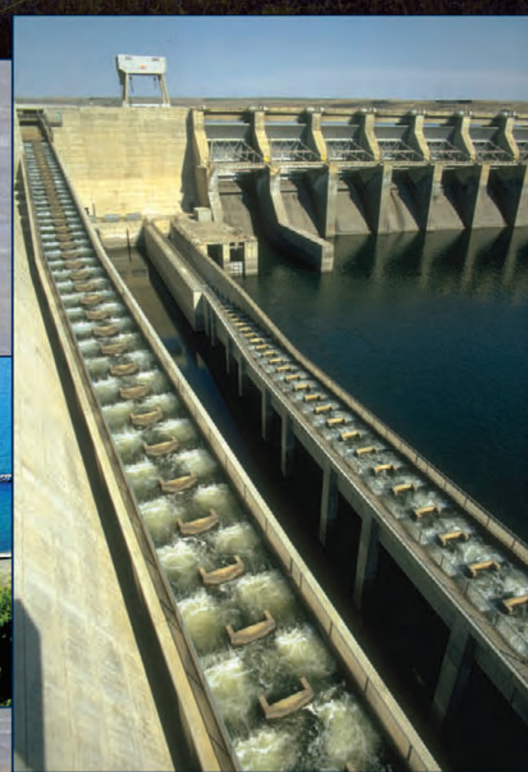

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National Management Measures
to Control Nonpoint Source Pollution from Hydromodification

Nonpoint Source Control Branch
Office of Wetlands, Oceans and Watersheds
U.S. Environmental Protection Agency
Office of Water

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Disclaimer

This document provides technical guidance to States, Territories, authorized Tribes, and the public for managing hydromodification and reducing associated NPS pollution of surface and ground water. At times, this document refers to statutory and regulatory provisions, which contain legally binding requirements. This document does not substitute for those provisions or regulations, nor is it a regulation itself. Thus, it does not impose legally-binding requirements on EPA, States, Territories, authorized Tribes, or the public and may not apply to a particular situation based upon the circumstances. EPA, State, Territory, and authorized Tribe decision makers retain the discretion to adopt approaches to manage hydromodification and reduce associated NPS pollution of surface and ground water on a case-by-case basis that differ from this guidance where appropriate. EPA may change this guidance in the future.

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Introduction

The Nation's aquatic resources are among its most valuable assets. Although environmental protection programs in the United States have improved water quality during the past 30 years, many challenges remain. Significant strides have been made in reducing the impacts of discrete pollutant sources, but some aquatic ecosystems remain impaired, due in part to complex pollution problems caused by nonpoint source (NPS) pollution (for more information on NPS pollution, go to EPA's website at http://www.epa.gov/owow/nps). Of special concern are the problems in our streams, lakes, estuaries, aquifers, and other water bodies caused by runoff that is inadequately controlled or treated. These problems include changes in flow, increased sedimentation, higher water temperature, lower dissolved oxygen, degradation of aquatic habitat structure, loss of fish and other aquatic populations, and decreased water quality due to increased levels of nutrients, metals, hydrocarbons, bacteria, and other constituents.

What is Hydromodification?

> *Hydromodifications (*or hydrologic modifications) are activities that disturb natural flow patterns of surface water and groundwater and have been defined as "...activities which alter the geometry and physical characteristics of streams in such a way that flow patterns change."

Examples of hydromodifications to streams include dredging, removing snags,[1] straightening, and, in some cases, complete stream relocation. Other examples include construction in or along streams, construction and operation of dams and impoundments, channelization in streams, dredging, and land reclamation activities. Some indirect forms of hydromodification, such as erosion along streambanks or shorelines, are caused by the introduction or maintenance of dams and other activities, including many upland activities, that change the natural physical properties of a stream.

The following definitions are offered to clarify some key terms used throughout this document:

> Hydromodification can be defined as changes in a river or stream channel resulting either in an increase or decrease in the usual supply of water flowing through the channel, or in a change to the usual physical characteristics of the water or of the channel. USEPA (1993) defines hydromodification as the "alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources." For this document, based on the above definitions, hydromodification refers to an activity or group of activities that alter the geometry and physical characteristics of a stream or river in such a way that the flow patterns change.
>
> Channelization and channel modification include activities such as straightening, widening, deepening, and clearing channels of debris. Categories of channelization and channel modification projects include flood control and

[1] A tree or branch embedded in a lake or stream bed and constituting a hazard to navigation; a standing dead tree.

drainage, navigation, sediment control, infrastructure protection, mining, channel and bank instability, habitat improvement/enhancement, recreation, and flow control for water supply (Watson et al., 1999). Channelization activities can play a critical role in NPS pollution by increasing the timing and delivery of pollutants, including sediment, that enter the water. Channelization can also be a cause of higher flows during storm events, which potentially increases the risk of flooding.

Dams[2] are artificial barriers on waterbodies that impound or divert water and are built for a variety of purposes, including flood control, power generation, irrigation, navigation, and to create ponds, lakes, and reservoirs for uses such as livestock watering, municipal water supply, fish farming, and recreation. They can contribute to NPS pollution by altering flows, which ultimately can cause impacts to water quality (changes to temperature or dissolved gases) and biological/habitat (disruption of spawning or altering of plant and benthic communities) above and below the dam.

Streambank and shoreline erosion are the wearing away of material in fastland (area landward of the bank) along non-tidal streams and rivers and the loss of beach fastland in tidal portions of coastal bays or estuaries. Streambank erosion occurs when the force of flowing water in a river or stream exceeds the ability of soil and vegetation to hold the banks in place. Eroded material is carried downstream and redeposited in the channel bottom or in point bars located along bends in the waterway. In large open waterbodies, such as the Great Lakes or coastal bays and estuaries, waves and currents sort coarser sands and gravels from eroded bank materials and move them in both directions along the shore away from the area undergoing erosion through a process called littoral drift. It is important to note that streambank and shoreline erosion are natural processes and that natural background levels of erosion also exist. However, human activities along or adjacent to streambanks or shorelines may increase erosion and other nonpoint sources of pollution.

Why is NPS Guidance on Hydromodification Important?

Hydromodification is one of the leading sources of impairment in our nation’s waters. According to the *National Water Quality Inventory: 2000 Report to Congress* (USEPA, 2002a), there are almost 3.7 million miles of rivers and streams[3] in the United States. Approximately 280,000

[2] Dams are defined according to Title 33 of the Code of Federal Regulations, section 222.6(h) (2003) as all artificial barriers together with appurtenant works which impound or divert water and which (1) are 25-feet or more in height or (2) have an impounding capacity of 50 acre-feet or more. Barriers that are six-feet or less in height, regardless of storage capacity or barriers that have a storage capacity at maximum water storage elevation of fifteen acre-feet or less regardless of height are not included. Federal regulations define dams for the purpose of ensuring public safety. For example, 33CFR222.6 states objectives, assigns responsibilities, and prescribes procedures for implementation of a National Program for Inspection of Non-Federal Dams. Most states use this or a very similar definition, which creates a category of dams that requires some form of inspection to ensure that they are structurally sound. Dams smaller than those defined above, such as those used to create farm ponds, are authorized under the NRCS program.
[3] Approximately 700,000 miles (19%) of the total 3.7 million miles of rivers and streams in the United States were assessed for the *National Water Quality Inventory: 2000 Report to Congress* (USEPA, 2002a).

miles of assessed rivers and streams in the United States are impaired for one or more designated uses, which includes aquatic life support, fish consumption, primary contact recreation, secondary contact, drinking water supply, and agriculture. Many of the pollutants causing impairment are delivered to surface and ground waters from diffuse sources, such as agricultural runoff, urban runoff, hydrologic modification, and atmospheric deposition of contaminants. The leading causes of beneficial use impairment (partially or not supporting one or more uses) are nutrients, sediment, pathogens (bacteria), metals, pesticides, oxygen-depleting materials, and habitat alterations (USEPA 2002a).

The *National Water Quality Inventory: 2000 Report to Congress* (USEPA, 2002a) identified hydrologic modifications (i.e., hydromodification) as a leading source of water quality impairment in assessed surface waters. Of the 11 pollution source categories listed in the report, hydromodification was ranked as the second leading source of impairment in assessed rivers, second in assessed lakes, and sixth in assessed estuaries (Table I.1). Three major types of hydromodification activities—channelization and channel modification, dams, and streambank and shoreline erosion—change a waterbody's physical structure as well as its natural functions.

Table I.1. Leading Sources of Water Quality Impairment Related to Human Activities for Rivers, Lakes, and Estuaries (USEPA, 2002a)

	Rivers and Streams	Lakes, Ponds, and Reservoirs	Estuaries
Sources[b]	Agriculture (48%)[a]	Agriculture (41%)	Municipal Point Sources (37%)
	Hydrologic Modification (20%)[c]	**Hydrologic Modification (18%)**	Urban Runoff/Storm Sewers (32%)
	Habitat Modification (14%)[d]	Urban Runoff/Storm Sewers (18%)	Industrial Discharges (26%)
	Urban Runoff /Storm Sewers (13%)	Nonpoint Sources (14%)	Atmospheric Deposition (23%)
	Forestry (10%)	Atmospheric Deposition (13%)	Agriculture (18%)
	Municipal Point Sources (10%)	Municipal Point Sources (12%)	**Hydrologic Modification (14%)**
	Resource Extraction (10%)	Land Disposal (10%)	Resource Extraction (12%)

[a] Values in parentheses represent the approximate percentage of surveyed river miles, lake acres, or estuary square miles that are classified as impaired due to the associated sources.
[b] Excluding unknown, natural, and "other" sources.
[c] Hydrologic modifications include flow regulation and modification, dredging, and construction of dams. These activities may alter a lake's habitat in such a way that it becomes less suitable for aquatic life (USEPA, 2002a).
[d] Habitat modifications result from human activities, such as flow regulation, logging, and land-clearing practices. Habitat modifications—changes such as the removal of riparian (stream bank) vegetation—can make a river or stream less suitable for the organisms inhabiting it (USEPA, 2002a).

Purpose and Scope of the Guidance

National summaries, such as those shown in Table I.1, are useful in providing an overview of the magnitude of problems associated with hydromodification. Solutions, however, are usually applied at the local level. For example, in Maryland, the Shore Erosion Task Force, after investigating shore erosion in the state, published recommendations to be implemented under a Comprehensive Shore Erosion Control Plan. To initiate statewide planning, the Maryland

Department of Natural Resources established partnerships with two coastal counties that were significantly affected by shoreline erosion. These state-local partnerships enable the state to better identify and correct shoreline erosion problems throughout Maryland (MDNR, 2001).

State and local elected officials and agencies, landowners, developers, environmental and conservation groups, and others play a crucial role in working together for protecting, maintaining, and restoring water resources that are impacted by hydromodification activities. These local efforts, in aggregate, form the basis for changing the status of hydromodification as a national problem.

This guidance document provides background information about NPS pollution and offers a variety of solutions for reducing NPS pollution resulting from hydromodification activities. The background information and solutions include

- Sources of NPS pollution and how the generated pollutants enter the Nation's waters
- A discussion on the broad concept of assessing and addressing water quality problems on a watershed level
- Presentation of up-to-date technical information about how certain types of NPS pollution can be reduced most effectively through the implementation of these management measures

The primary goal of this guidance document is to provide technical assistance to states, territories, tribes, and the public for managing hydromodification and reducing associated NPS pollution of surface and ground water. The document describes examples of the implementation of practices that can be used to reduce NPS pollution from activities associated with channelization and channel modification, dams, and streambank and shoreline erosion.

Activities to Control NPS Pollution

Historical Perspective

During the first 15 years of the national program to abate and control water pollution (1972–1987), EPA and the states focused most of their water pollution control activities on traditional point sources, which are stationary locations or fixed facilities from which pollutants are discharged; any single identifiable source of pollution; e.g. a pipe, ditch, ship, ore pit, or factory smokestack. EPA and the states have regulated these point sources through the National Pollutant Discharge Elimination System (NPDES) permit program established by Section 402 of the Clean Water Act. The NPDES program functions as the primary regulatory tool for assuring that state water quality standards are met. NPDES permits, issued by an authorized state or EPA, contain discharge limits designed to meet water quality standards and national technology-based effluent regulations. For more information on the NPDES program, refer to EPA's NPDES website at http://cfpub.epa.gov/npdes.

In 1987, in view of the progress achieved in controlling point sources and the growing national awareness of the increasingly dominant influence of NPS pollution on water quality, Congress amended the Clean Water Act to focus greater national efforts on nonpoint sources.

Federal Programs and Funding

The Clean Water Act establishes several reporting, funding, and regulatory programs that address pollutants carried in runoff that is not subject to confinement or treatment. These programs relate to watershed management and nonpoint source control. Readers are encouraged to use the information contained in this guidance to develop nonpoint source management programs/plans that comprehensively address the following EPA reports and programs:

- *Section 319 Grant Program*. Under Section 319 of the Clean Water Act, EPA awards funds to states and eligible tribes to implement NPS management programs. These funds can be used for projects that address nonpoint source related sources of pollution, including hydromodification. More information about the Section 319 program is provided at http://www.epa.gov/owow/nps/cwact.html.

- *Section 404 Discharge of Dredged and Fill Material*. Under section 404 of the Clean Water Act, persons planning to discharge dredged or fill material to wetlands or other waters of the United States generally must obtain authorization for the discharge from the United States Army Corps of Engineers (USACE), or a state approved to administer the section 404 program. Such authorization can be through issuance of an individual permit, or may be subject to a general permit, which applies to certain categories of activities having minimal adverse environmental effects. Implementation of Section 404 is shared between the USACE and EPA. The USACE is responsible for reviewing permit applications and deciding whether to issue or deny permits. EPA, in consultation with the USACE, develops the section 404(b)(1) guidelines, which are the environmental criteria that the USACE applies when deciding whether to issue permits. EPA also has authority under section 404(c) to “veto” USACE issuance of a permit in certain cases, and has final authority on the scope of waters of the United States protected under the Clean Water Act. More information about the 404 program is provided at http://www.epa.gov/owow/wetlands.

- *Clean Water State Revolving Fund*. The Clean Water State Revolving Fund (CWSRF) program is an innovative method of financing environmental projects. Under the program, EPA provides grants or “seed money” to all 50 states plus Puerto Rico to capitalize state loan funds. The states, in turn, make loans to communities, individuals, and others for high-priority water quality activities. As money is paid back into the revolving fund, new loans are made to other recipients. When funded with a loan from this program, a project typically costs much less than it would if funded through the bond market. Many states offer low or no interest rate loans to small and disadvantaged communities. In recent years, state programs have begun to devote an increasing volume of loans to nonpoint source, estuary management, and other water-quality projects. Eligible NPS projects include almost any activity that a state has identified in its nonpoint source management plan. Such activities include projects to control runoff from agricultural land; conservation tillage and other projects to address soil erosion; development of streambank buffer zones; and wetlands protection and restoration. Additional information about CWSRF is available at http://www.epa.gov/OWM/cwfinance/cwsrf/index.htm.

- *Total Maximum Daily Loads*. Under section 303(d) of the Clean Water Act, states are required to compile a list of impaired waters that fail to meet any of their applicable water quality standards or cannot support their designated or existing uses. This list, called a 303(d) list, is submitted to Congress every 2 years, and states are required to develop a Total Maximum Daily Load (TMDL) for each pollutant causing impairment for waterbodies on the list. More information on the TMDL program and 303(d) lists is provided at http://www.epa.gov/owow/tmdl.

- *Water Quality Certification.* Section 401 of the Clean Water Act requires that any applicant for a federal license or permit to conduct any activity that "may result in any discharge" into navigable waters must obtain a certification from the state or tribe in which the discharge originates that the discharge will comply with various provisions of the Clean Water Act, including sections 301 and 303. The federal license or permit may not be issued unless the state or tribe has granted or waived certification. The certification shall include conditions, e.g., "effluent limitations or other limitations" necessary to assure that the permit will comply with the state's or tribe's water quality standards or other appropriate requirements of state or tribal law. Such conditions must be included in the federal license or permit.

- *National Estuary Program.* Under the National Estuary Program, states work together to evaluate water quality problems and their sources, collect and compile water quality data, and integrate management efforts to improve conditions in estuaries. To date, 28 estuaries have been accepted into the program. Estuary programs can be an excellent source of water quality data and can provide information on management practices. More information on the National Estuary Program is provided at http://www.epa.gov/nep.

- *Safe Drinking Water Act.* Many areas, especially urban fringe areas, need to maintain or improve the quality of surface and ground waters that are used as drinking water sources. This act requires states to develop Source Water Assessment Reports and implement Source Water Protection Programs. Low- or no-interest loans are available under the Drinking Water State Revolving Fund (SRF) Program. More information about the Safe Drinking Water Act and Source Water Protection Programs can be found at http://www.epa.gov/safewater/sdwa/index.html and http://www.epa.gov/safewater/protect.html.

Two excellent resources for learning more about the Clean Water Act and the many programs established under it are *The Clean Water Act: An Owner's Manual* (Killam, 2005) and *The Clean Water Act Desk Reference* (WEF, 1997).

Watershed Approach

EPA recommends the use of a watershed approach as the key framework for dealing with problems caused by runoff and other sources that impair surface waters (USEPA, 1998). The watershed protection approach is a comprehensive planning process that considers all natural resources in the watershed, as well as social, cultural, and economic factors. Using a watershed approach, multiple stakeholders integrate regional and locally-led activities with local, State, Tribal, and Federal environmental management programs. The watershed approach should address the following:

- Pollutants for which there are currently no numeric standards (including nutrients and clean sediments)
- Healthy aquatic habitats (including wetlands)
- Coastal and marine waters
- Invasive species and other stressors

EPA works with Federal agencies, States, Tribes, local communities, and non-governmental sectors to make a watershed approach the key coordinating framework of planning, restoration, and protection efforts to achieve “clean and safe” water and healthy aquatic habitat.

The watershed approach framework can be applied to address impacts caused by hydromodification activities throughout a watershed. Additionally, the watershed approach can help to identify and address problems within a watershed that increase NPS pollution associated with hydromodification activities.

Major elements of successful watershed approaches involve:

- Focusing on hydrologically-defined areas—watersheds and aquifers have hydrologic features that converge to a common point of flow; watersheds range in size from very large (e.g., the Mississippi River Basin) to a drainage basin for a small creek.

- Using an integrated set of tools and programs (regulatory and voluntary, Federal/State/Tribal/local and non-governmental sectors; innovation; communication and technical assistance; and sound science and information) to address the myriad problems facing the Nation’s water resources, including nonpoint source and point source pollution, habitat degradation, invasive species, and air deposition of pollutants (e.g., mercury and nutrients).

- Involving all parties that have a stake or interest in developing collaborative solutions to a watershed’s water resource problems.

- Using an iterative planning or adaptive management process of assessment, setting environmental and water quality and habitat goals (e.g., water quality standards), planning, implementation, and monitoring and ensuring that plans and implementation actions are revised to reflect new data.

- Breaking down barriers between plan development and implementation to enhance prospects for success.

A key attribute of the watershed approach is that it can be applied with equal success to large- and small-scale watersheds. Federal agencies, states, interstate commissions, and tribes usually apply the approach on larger scales, such as watersheds 100 square miles in size. Local agencies and urban communities can apply the approach to watersheds as small as 1 square mile in size.

Although specifics may vary from large scale to small scale, the basic goals of the watershed approach remain the same—protecting, maintaining, and restoring water resources. Local runoff management program officials must be especially conscious of watershed scale when planning and implementing specific management practices. For example, nonstructural practices, such as stream protection ordinances and public education campaigns, are usually applied community wide. Consequently, the results benefit many small watersheds. In contrast, structural practices, such as soil bioengineering, usually provide direct benefits to a single stream. Regional structural management practices such as headland breakwater systems for larger watersheds can be used, but they do not protect smaller contributing streams. Given limited resources, program officials must often analyze cost and benefits and choose between large- and small-scale practices. Often, a combination of nonstructural and structural practices is the most cost effective approach.

An example of the watershed approach being used for hydromodification activities is the South Myrtle Creek Ditch Project. South Myrtle Creek, which flows into the South Umpqua River in Oregon, was historically populated with cutthroat trout (*Oncorhynchus clarki*) and coho salmon (*Oncorhynchus kisutch*). However, since the early 20th century, diversion structures, used primarily for providing water for irrigating agricultural crops, have blocked the passage of fish through its waters (USEPA, 2002c). One example of the diversion structures was a diversion dam with a concrete apron, which was installed in a portion of South Myrtle Creek to raise the water level in an impoundment to provide irrigation water for adjacent and downstream landowners. During the summer, water levels in the creek would elevate 14 feet above natural levels and were diverted into a 2.5 mile irrigation ditch. Ultimately, hydromodification of this stream caused flow modifications and high stream temperatures, which degraded water quality for the native trout and salmon populations.

In 1998 one of the landowners initiated a project to restore flow and improve water quality in South Myrtle Creek. The project used the three guiding principles of the watershed approach to restore the health of the creek.

- *Partnership*. The project was a collaborative effort of landowners, who donated services and supplies. The project received funding and support from government agencies, such as the U.S. Fish and Wildlife Service, the Oregon Water Resources Department, the Oregon Watershed Enhancement Board, the Bureau of Land Management, the Natural Resources Conservation Service, and the Douglas County Watermaster.

- *Geographic focus*. Resource management activities were directed specifically to the creek and the drainage ditch, where flow restoration and improved water quality were desired.

- *Sound management techniques based on strong science and data*. An assessment of South Myrtle Creek identified water quality problems from flow modification and high stream temperatures as the priority problems in the creek. The diversion dam and concrete apron were found to be causing the problems. Landowners, the Water Resources Department, and the Watershed Enhancement Board developed a plan, the goal of which was to restore flow and improve water quality in the creek. The plan was implemented by removing the diversion dam and concrete apron. The irrigation system was switched to a sprinkler type system, which is more efficient than the original ditch irrigation. In addition, the denuded riparian area was revegetated to help lower stream temperatures and new seedlings were protected with fencing to keep away livestock.

With the cooperation of the landowners, the county and state governments, and other interested parties, the South Myrtle Creek Ditch Project was a success. Water temperatures have improved and flows have increased by 2.5 cubic feet per second during the summer. Restoration of the streambed to its historical level has allowed passage of salmon and trout to the 10 miles of stream above the dam (USEPA, 2002c). Additional information about the project is available at http://www.epa.gov/owow/nps/Section319III/OR.htm.

Introduction to Management Measures

Management measures are implemented to control nonpoint source pollution for a variety of purposes, including protection of water resources, aquatic wildlife habitat, and land downstream from increased pollution and flood risks. Management measures control the delivery of NPS pollutants to receiving water resources by:

- Minimizing pollutants available (source reduction)
- Retarding the transport and/or delivery of pollutants, either by reducing water transported, and thus the amount of the pollutant transported, or through deposition of the pollutant
- Remediating or intercepting the pollutant before or after it is delivered to the water resource through chemical or biological transformation

Management measures are generally designed to control a particular type of pollutant from specific land uses. The intent of the six management measures in this guidance document is to provide information for addressing and considering the NPS pollution potential associated with hydromodification activities in all water pollution control activities in a watershed. Implementation of management measures can minimize and control hydromodification NPS pollution through erosion and sediment control, chemical and pollutant control, management of instream and riparian habitat restoration, and protection of surface water quality.

This document also lists and describes management practices for each management measure. Management practices are specific actions taken to achieve, or aid in the achievement of, a management measure. A more familiar term might be best management practice (BMP). The word “best” has been dropped for the purposes of this guidance (as it was in the Coastal Management Measures Guidance) because the adjective is too subjective. The “best” practice in one area or situation might be entirely inappropriate in another area or situation. The practices listed in this document have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measures. EPA recognizes that there is often site-specific, regional, and national variability in the selection of appropriate practices, as well as in the design constraints and pollution control effectiveness of practices. The practices presented for each management measure are not all-inclusive. States or local agencies and communities might wish to apply other technically and environmentally sound practices to achieve the goals of the management measures.

Channelization and Channel Modification

Channelization can cause changes, such as a reduction in freshwater supply, and results in the faster delivery of pollutants. Channel modification might result in a combination of harmful effects (higher flows or increased risk of flooding) and beneficial effects (prevent the increase in delivery of sediment to marshes or enhance flushing in a stream channel, which would help improve fish spawning activities). The two management measures for channelization and channel modification are intended to protect waterbodies by ensuring proper planning before the proposed project is implemented, which helps to correct or prevent detrimental changes to the instream and riparian habitat. Implementation of the management measures can also ensure that operation and maintenance programs for existing projects improve physical and chemical characteristics of surface waters when possible.

> **Management Measure for Physical and Chemical Characteristics of Surface Water:** Ensure that the planning process for new hydromodification projects addresses changes to physical and chemical characteristics of surface waters that may occur as a result of the proposed work. For existing projects, ensure that operation and maintenance programs use any opportunities available to improve the physical and chemical characteristics of surface waters.

> **Management Measure for Instream and Riparian Habitat Restoration:** Correct or prevent detrimental changes to instream and riparian habitat from the impacts of channelization and channel modification projects, both proposed and existing.

Dams

When dams are constructed, the turbidity and sedimentation in a waterway is often increased. Construction activities, chemical spills during dams operation or maintenance, and reduced downstream flushing alters the nature of the waterbody. The management measures for dams are intended to be applied to the construction of new dams, as well as any construction activities associated with the maintenance of dams. They can be applied to dam operations that result in the loss of desirable surface water quality, and instream and riparian habitat.

> **Management Measure for Erosion and Sediment Control:** Prevent sediment from entering surface waters during the construction or maintenance of dams.

> **Management Measure for Chemical and Pollutant Control:** Prevent downstream contamination from pollutants associated with dam construction and operation and maintenance activities.

> **Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat:** Protect the quality of surface waters and aquatic habitat in reservoirs and in the downstream portions of rivers and streams that are influenced by the quality of water contained in the releases (tailwaters) from reservoir impoundments.

Streambank and Shoreline Erosion

Nonpoint source pollution might result from the erosion of streambanks and shorelines when sediment eroded upstream is deposited downstream. Habitats can be buried and wetlands can be filled. As runoff upstream increases, more erosion results on downstream streambanks. The streambank and shoreline erosion management measure promotes the necessary actions required to correct streambank and shoreline erosion where it must be controlled. Because erosion is a natural process, this management measure is not intended to be applied to all erosion occurring on streambanks and shorelines.

> **Management Measure for Eroding Streambanks and Shorelines:** Protect streambanks and shorelines from erosion and promote institutional measures that establish minimum setback requirements or measures that allow a buffer zone to reduce concentrated flows and promote infiltration of surface water runoff in areas adjacent to the shoreline.

Document Organization

This document is divided into three sections (Channelization and Channel Modification, Dams, and Streambank and Shoreline Erosion), which focus on individual management measures that are specific to each type of hydromodification activity. Each section introduces the management measure(s) for the particular topic and presents a range of management practices that potentially can be implemented to achieve the management measure. Boxed text and case studies throughout the chapters highlight important concepts and provide real-life examples of how select management practices have been implemented within communities. When available, information concerning effectiveness and costs of practices is included.

The document also includes references and resources. The *References* section documents all literature cited throughout the document. The *Resources* section includes an updated list of documents, technical guidance, journals, funding information, general hydromodification Internet links, listservers, and educational materials. Two appendices are included in this document: Federal, State, Nonprofit, and Private Financial and Technical Assistance Programs (Appendix A) and U.S. Environmental Protection Agency Contacts (Appendix B).

Planning and Balance

Project planning and analysis are essential parts of success when using a methodological framework such as the watershed approach to minimize environmental impacts of NPS pollutants associated with hydromodification activities. One example of a planning process is explained in the EPA document *Ecological Restoration: A Tool to Manage Stream Quality* (USEPA, 1995a). This document outlines the key steps in the ecological restoration decision framework as:

- Identification of impaired or threatened watersheds
- Inventory of the watershed
- Identification of the restoration goals
- Selection of candidate restoration techniques

- Implementation of selected restoration techniques
- Monitoring

Other EPA guidance documents offer similar approaches to the restoration planning process, including *Community-Based Environmental Protection: A Resource Book for Protecting Ecosystems and Communities* (USEPA, 1997a) Both guidance documents offer a variety of case studies to provide readers with examples of the frameworks as they are applied to real-world situations. EPA's draft *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* also provides useful planning information related to watershed plans.

9 Elements of Watershed Planning

EPA has identified a minimum of nine elements that are critical for achieving improvements in water quality. EPA requires that these nine elements be addressed for section 319-funded watershed plans and strongly recommends that they be included in all other watershed plans that are intended to remediate water quality impairments. Additional information is available at from FY 2004 Guidelines for the Award of Section 319 Nonpoint Source Grants to States and Territories *at http://www.epa.gov/owow/nps/cwact.html. The nine elements are listed below:*

a. Identification of causes of impairment and pollutant sources or groups of similar sources that need to be controlled to achieve needed load reductions, and any other goals identified in the watershed plan. Sources that need to be controlled should be identified at the significant subcategory level along with estimates of the extent to which they are present in the watershed (e.g., X linear miles of eroded streambank needing remediation).

b. An estimate of the load reductions expected from management measures.

c. A description of the nonpoint source management measures that will need to be implemented to achieve load reductions and a description of the critical areas in which those measures will be needed to implement this plan.

d. Estimate of the amounts of technical and financial assistance needed, associated costs, and/or the sources and authorities that will be relied upon to implement this plan.

e. An information and education component used to enhance public understanding of the project and encourage their early and continued participation in selecting, designing, and implementing the nonpoint source management measures that will be implemented.

f. Schedule for implementing the nonpoint source management measures identified in this plan that is reasonably expeditious.

g. A description of interim measurable milestones for determining whether nonpoint source management measures or other control actions are being implemented.

h. A set of criteria that can be used to determine whether loading reductions are being achieved over time and substantial progress is being made toward attaining water quality standards.

i. A monitoring component to evaluate the effectiveness of the implementation efforts over time, measured against the criteria established under item h immediately above.

The Natural Resources Conservation Service (NRCS) is also a source of information for planning. NRCS provides assistance through their Watershed Protection and Flood Prevention Program, whose purpose is to assist federal, state, local agencies, local government sponsors, tribal governments, and program participants to protect and restore watersheds from damage caused by erosion, floodwater, and sediment, to conserve and develop water and land resources, and to solve natural resource and related economic problems on a watershed basis. The program provides technical and financial assistance to local people or project sponsors, builds partnerships, and requires local and state funding contribution. Additional information about this program, as well as contact information is available at http://www.nrcs.usda.gov/programs/watershed.

NRCS uses locally-led conservation programs, which are an extension of the agency's traditional assistance to individual farmers and ranchers for planning and installing conservation practices for soil erosion control, water management, and other purposes. Through this effort, local people, generally with the leadership of conservation districts along with NRCS technical assistance, will assess their natural resource conditions and needs, set goals; identify ways to solve resource problems, utilize a broad array of programs to implement solutions, and measure their success.

Many of the management measures and practices recommended by EPA to reduce the NPS pollutant impacts associated with hydromodification activities stress the need to incorporate planning as a tool. States, local governments, or community groups should begin the planning process early when trying to determine how to address a particular NPS issue associated with a new or existing hydromodification project. The planning process should bring key stakeholders together so that a variety of options can be explored to adequately define the problem and potential solutions. Once the issues are identified according to the various perspectives, project goals can be established to solve one or more environmental problems.

One important part of the planning process is the identification of the goals of the different stakeholders. Once these goals, which are sometimes different for the different groups of stakeholders, are identified and defined, the planning team can strive to achieve a balance among the needs of the various stakeholders. Often restoration compromises can be made to meet differing goals of the stakeholders to achieve a balance of the needs of the different groups. For example, hydroelectric dams can be operated to produce minimum base flows downstream from the dam to support a variety of aquatic habitats, while still providing energy in a profitable manner. In addition, solutions that only allow for complete removal of the dam and restoration to preexisting stream conditions may not be possible because of other changes in the watershed (e.g., urbanization, other hydromodification projects, or the need for affordable and environmentally friendly electricity). A compromise solution that enables the dam to continue to operate while minimizing environmental impacts and to enhance critical downstream habitats that support a desirable fish population may be the best solution.

Creating Opportunities

Part of the planning process and achievement of balance when evaluating techniques for restoring areas impacted by NPS pollution associated with hydromodification activities can be termed "creating opportunities." For example, an opportunity may be found by working with stakeholders such as local homeowners who are concerned about the unsightly algae present in a community reservoir. Reducing runoff containing an abundant supply of nutrients from lawns surrounding the reservoir may lead to reductions in the algal bloom. The operations of the dam that creates the reservoir may be changed to enhance reservoir quality, as well as the quality of water being released from the dam. Changes in land use that result in increasing the permeability of land adjacent to a channelized stream can reduce the overall volume and velocity of water in the stream. As flooding conditions are reduced, “hard” structures like bulkheads can be replaced with softer, vegetative solutions along the stream channel. The combination of reduced scouring flows associated with the greater stream velocities and vegetated channel banks can lead to improved instream ecological conditions. There are many other possible opportunities waiting to be found and implemented when projects are evaluated at the watershed level.

Section 1 Channelization and Channel Modification

Channelization and channel modification describe river and stream channel engineering undertaken for flood control, navigation, drainage improvement, and reduction of channel migration potential. Activities that fall into this category include straightening, widening, deepening, or relocating existing stream channels and clearing or snagging operations. These forms of hydromodification typically result in more uniform channel cross-sections, steeper stream gradients, and reduced average pool depths. Channelization and channel modification also refer to the excavation of borrow pits, canals, underwater mining, or other practices that change the depth, width, or location of waterways, or embayments within waterways.

Channelization and channel modification activities can play a critical role in nonpoint source pollution by increasing the downstream delivery of pollutants and sediment that enter the water. Some channelization and channel modification activities can also cause higher flows, which increases the risk of downstream flooding.

Channelization and channel modification can:

- Disturb stream equilibrium
- Disrupt riffle and pool habitats
- Create changes in stream velocities
- Eliminate the function of floods to control channel-forming properties
- Alter the base level of a stream (streambed elevation)
- Increase erosion and sediment load

Many of these impacts are related. For example, straightening a stream channel can increase stream velocities and destroy downstream pool and riffle habitats. As a result of less structure in the stream to retard velocities, downstream velocities may continue to increase and lead to more frequent and severe erosion.

There are often differing views defining the stability of a stream channel. From a navigation perspective, the stream channel is considered stable if shipping channels are maintained to enable safe movement of vessels. Landowners with property adjacent to a stream might consider the stream to be stable if it does not flood and erosion is minimal. Ecologists might find some erosion of streambanks and meandering channels to be a part of natural evolution (i.e., changes that are not induced by humans) and consider long-term changes like these to be quite acceptable (Watson et al., 1999). In any case, new and existing channelization projects should be evaluated with these differing perspectives in mind and a balance of these perspectives taken into account when constructing or maintaining a project. Often, multiple priorities can be maintained with good up-front planning and communication among the different stakeholders involved.

There are four key characteristics of a channel, which are channel slope, depth, width, and planform, that may adjust to reflect changes in basin inputs. The factors that affect the basin characteristics were described in Watson et al. (1999) and include:

- The geology of the basin and channel
- Water and sediment discharged to the channel
- Characteristics of the contributing watershed (e.g., slope, land use, vegetative cover, soils)
- Climate

The stream channel constantly tries to adjust to changes in these factors by changing slope, depth, width, and planform. When the channel is able to maintain these adjustments without agrading (depositing) or degrading (eroding), it is considered to be in dynamic equilibrium (Watson et al., 1999). When disturbed, the channel attempts to regain a state of equilibrium by making adjustments, which can consist of changes to the channel elevation by aggradation or degradation or in the channel planform (Biedenharn et al., 1997). Alterations to a stream channel can result in local or system-wide channel instability (FISRWG, 1998).

Hydromodification activities, such as channelization and channel modification, can affect a stream channel's state of equilibrium, which is related to flow and the height of the water surface. It is important to note that the stream is not static and is constantly adjusting to the changes, which could lead to instability, that naturally occur. Changes caused by (or exacerbated by) human activities may upset a critical balance and lead to a disruption of the dynamic equilibrium of the stream channel. When the factors affecting equilibrium become unbalanced, the stream attempts to regain equilibrium and nonpoint source pollution can result.

Stream channels are often characterized by a series of riffle, pool, and run habitats (Figure 1.1). Riffles are shallow, turbulent, and swiftly flowing stretches of water that flow over partially or totally submerged rocks. These areas are well oxygenated and have a "patchy distribution of organisms," which means that different types of organisms are naturally found in different parts of the riffle. Pools are distinct habitats within the stream where the velocity of the water is reduced and the depth of the water is greater than most other stream areas. Sediments can deposit in pools, which can lead to the formation of islands, shoals, or point bars. Sediment can also result in the complete filling of pools. A pool usually has soft bottom sediments. The four basic types of pools are large-shallow, large-deep, small-shallow, and small-deep. A stream with many pool types will support a wide variety of aquatic species. Runs are sections of a stream with a relatively high velocity and

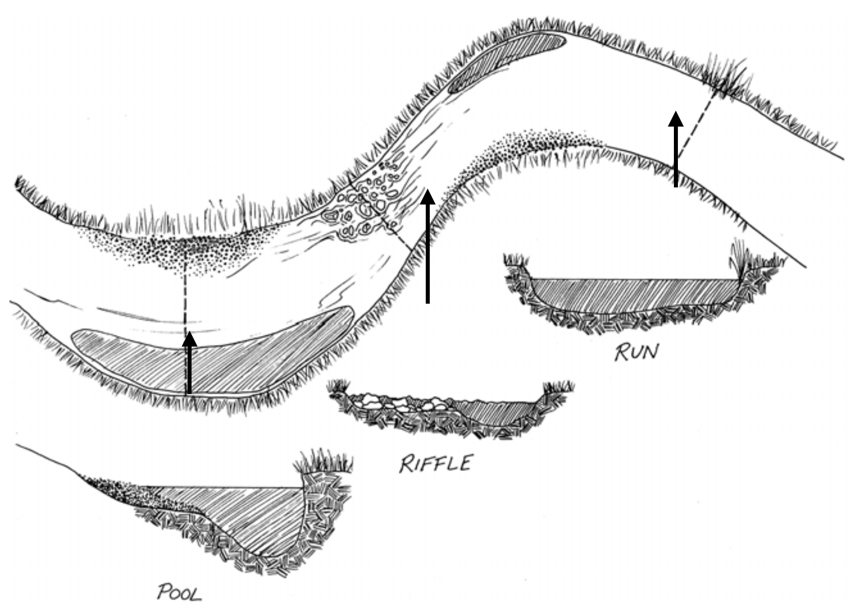


Figure 1.1 Overview of a Pool, Riffle, and Run (USEPA, 1997b)

with little or no turbulence on the surface of the water. Pools, riffles, and runs create a mixture of flows and depths and provide a variety of habitats to support fish and invertebrate life (USEPA, 1997b). Channelization projects can disrupt the mechanisms that lead to the creation and natural maintenance of these riverbed features.

Channelization, which involves straightening of the stream channel, decreases the length of a channel and effectively increases the slope of the channel by decreasing the length the channel has to drop a given vertical distance. An increase in the slope of a channel results in higher water velocities, which can have an effect on the physical and biological characteristics of a channel (Simons and Senturk, 1992). Stream modifications to reduce flood damage, such as levees and floodwalls, often narrow the stream width, increasing the velocity of the water and thus its erosive potential downstream (FISRWG, 1998).

The slope of a stream is one of the most important factors in determining a stream's ability to do work. A stream with a steep slope is generally much more active in terms of bank erosion, bar building, and sediment movement than a stream with a lower slope (Biedenharn et al., 1997). The increase in the slope downstream produces an excess sediment transport capacity. The stream must adjust to this increased capacity by increasing its sediment load. This increased load will be derived from erosion of the banks and degradation or lowering of the channel bed.

If a channel is deepened or widened, however, the result can be a slower and/or shallower flow. In tidal areas, channel modification activities, such as deepening a channel to allow for larger ships to access a shoreline, may require frequent maintenance to remove accumulating sediment because of changes in flow patterns. Reduced stream velocities can result in more sediment deposits to a stream segment. When more sediment is deposited in an area of a stream, critical habitats can be buried, channels may become unstable, and flooding increase. Therefore, channelization projects must be carefully planned and executed to prevent serious changes from occurring in areas downstream or adjacent to the project.

In a naturally flowing stream, floods are responsible for such processes as redistributing sediment from the river bottom to form sandbars and point bar deposits. Stream channel modifications to reduce flood damage, such as levees and floodwalls, often narrow the stream width, increasing the velocity of the water and thus its erosive potential. This can lead to increased erosion of the streambank and shoreline in downstream locations (FISRWG, 1998).

Case Study: The Obion River

In the 1960s, the U.S. Army Corps of Engineers (USACE) began a project to channelize 119 miles of the Obion River in western Tennessee to reduce flooding that was inhibiting the productivity of agriculture in the lower bottomlands adjacent to the river. During the 1960s, 80 miles of the channel was enlarged, straightened, and cleared out, resulting in an increase in the water velocity along the channelized area and downstream. During storm events and other high flow periods, water from the channelized portion of the drainage basin is conveyed to downstream locations faster than before the project was completed and the stream channel cannot accommodate the increased volume, resulting in higher peak discharges and an increase in flood frequency. From May to October, the number of floods on the lower section of the Obion River increased 140 percent following channelization. However, the project did reduce flooding frequency and the average duration of the flood events has decreased due to the greater flow efficiency of the channel in the upper part of the river.

In 1990, construction on the remaining portion of the channel was discontinued by the state of Tennessee, with the denial of the water quality certification for the project. In 1992, however, the state of Tennessee requested that the project be reactivated and incorporate environmentally sensitive guidelines into its design. A steering committee made up of representatives from state and local agencies and local interest groups was formed. A Mission Plan, which incorporated a revised plan for the project was finished in 1994. The objective of the reformulated project included resolving the ecological and financial problems caused by stream channelization, restoring streams to their natural shape and floodplains to their natural hydroperiod, and designing and implementing demonstration projects. Douglas Smith, L.A. Turrini-Smith (Tennessee Dept. of Environment and Conservation), and Timothy Diehl (U.S. Geological Survey) have created a channel design based upon extensive geomorphic field surveys of a wide range of healthy river systems. An evaluation of demonstration projects on channels within the West Tennessee Tributaries project area was completed and approved in September 1996. Negotiations to allow for construction of the demonstration projects are on going. As of December 2001, 93 miles of the 119-mile project were completed and the remainder of the project is expected to be completed by September 2006.

Sources:
Shankman, D. and S. A. Samson. 1991. Channelization effects on Obion River flooding, Western Tennessee. *Water Resources Bulletin* 27:247-54.

Shankman, D. and T. B. Pugh. 1992. Discharge response to channelization of a coastal-plain stream. *Wetlands*, 12(3):157-162.

Smith, Douglas. California State University Monterey Bay. 2003. *Doug's Projects* http://home.csumb.edu/s/smithdouglas/world/Doug/html/projects.html. Accessed July 2003.

U.S. Army Corps of Engineers. *Environmental News.* http://www.mvr.usace.army.mil/PublicAffairsOffice/InternetNews/Environment/MVDIMprovesEnviro.htm. Accessed July 2003.

U.S Army Corps of Engineers; Memphis District. 2001. *West Tennessee Tributaries.* http://www.mvm.usace.army.mil/projects/westtntribs/home.htm. Accessed July 2003.

U.S. Environmental Protection Agency. 2002. *Lower Mississippi Valley Ecosystem Restoration Initiative.* http://www.epa.gov/region4/programs/cbep/lowmiss.html. Accessed July 2003.

Channelization can result in alterations to the base level of the stream, including channel downcutting or incision of a section of the stream, which raises the height of the floodplain relative to the riverbed and decreases the frequency of overbank flow. When streams reach flood stage and flow into the floodplain, velocities decrease. The reduction in overbank flow reduces sediment deposition and the sediment storage potential of the floodplain (Wyzga, 2001). A change in the downstream base level of a stream can create an unstable stream system (Biedenharn et al., 1997).

Channel modification and channelization can lead to increased erosion in some areas of the stream, which produces sediment. Sediment can be dislodged and transported directly from the waterbody's shoreline, bank, or bottom. Sediment being transported by a stream is referred to as the sediment load, which is further classified as the bed load (those particles moving on or near the bed, or bottom of the channel) and the suspended load (those particles moving in the water column).

> *Sediment is insoluble material suspended in water that consists mainly of particles derived from rocks, soil, and organic materials; a major nonpoint source pollutant to which other pollutants may attach (WEF, 2003).*

Because erosion is a natural process and significant quantities of sediments are being moved as a result of natural denudation, it would be unrealistic to expect complete control or elimination of sediment loads to receiving waters. However, it is feasible to control or manage excessive sediment loadings from various land use activities that would be detrimental to the quality of the receiving waterbodies and to the aquatic and terrestrial habitat. The types of erosion associated with channelization and channel modification that produce sediment are (1) destabilization of streambanks (2) increased flow, which carries more sediment downstream at a quicker rate, and (3) gully erosion.

The amount of force placed by the flow along a stream bank and streambed may vary considerably with no apparent effect on stabilization until some critical point is reached when the forces (i.e., pressure) exerted by the flowing water exceed the resisting forces of the bank or bed material and vegetation (USACE, 1994). The pressure will then cause the material to move and could result in dramatic erosion. As the streambed begins to erode away, the zone of increased slope and the resulting erosion will move upstream (Biedenharn et al., 1997). The increase in erosion upstream will result in increased aggradation or deposition further downstream. If there is a reduced channel capacity, downstream bank erosion and flooding can be exacerbated (refer to EPA's *National Management Measures to Control Nonpoint Source Pollution from Urban Areas* (http://www.epa.gov/owow/nps/urbanmm/index.html) (USEPA, 2005d) for more information). An increased channel capacity through widening or other measures can lead to a decrease in stream velocity and thus increased deposition within the channel that may further reduce stream capacity (Brookes, 1998).

Physical and Chemical Alterations

Channelization and channel modification activities can lead to a variety of physical and chemical changes to water bodies that are adjacent to and/or downstream of the channel modification. The various activities that fall into the category of channelization and channel modification, such as straightening, hardening, narrowing, or widening of stream channels and installation of culverts, can result in diverse physical and chemical impacts to water quality. The following discussion begins with a short description of some physical and chemical changes that occur from channelization and channel modification activities. It is important to remember that many of the physical and chemical changes are interrelated. For a more detailed discussion of the impacts associated with chemical and physical changes to surface waters, see *Restoration of Aquatic Ecosystems* (National Research Council, 1992).

The most significant physical impact is the movement or deposition of sediment. Sediment erodes from stream banks and beds, is washed downstream in faster moving water, deposited in areas of slower flows, and transported into new areas of streams or other receiving waters. Critical habitat can be changed when channelization or channel modification projects alter the established equilibrium of a stream and change sediment transport or deposition characteristics. Newly established stream equilibrium conditions may take some time to occur and have long-lasting effects to habitat and water quality conditions.

> *A study of the economic impact of excessive erosion and transport of sediment in surface water systems estimates the annual costs for damage due to sediment pollution in North America at approximately $16 billion (Osterkamp et al., 1998). Sediment pollution costs can be measured in physical damages, chemical damages, and biological damages. Physical damages include damages to water conveyance, treatment, and storage facilities, and interference with recreational and navigational use. Chemical damages include deposition and storage of nutrients, metals, and pesticides associated with eroded sediments. Biological damages include damage to aquatic habitat from the movement and storage of sediment (Osterkamp et al., 1998).*

Other physical impacts include changes in flow rates and patterns, temperature, dissolved oxygen concentrations, and turbidity. Some examples of physical changes that correspond to channelization and channel modification activities include:

- Channel deepening and straightening – increased velocities and flow rates
- Channel widening – shallower depths and increased temperatures
- Channel straightening and widening – reduced dissolved oxygen (resulting from reduced turbulance)
- Channel narrowing – increased erosion and turbidity
- Channel hardening – increased velocities and flow rates

A variety of chemicals can be introduced into surface waters when channelization and channel modification activities alter flow and sediment transport characteristics. Nutrients, metals, toxic organic compounds, pesticides, and organic materials can enter the water in eroding soils along banks and move throughout a stream as flow characteristics change. Changing temperatures and dissolved oxygen levels may lead to alterations in the bioavailability of metals and toxic organics. Complex chemical conditions can significantly change when stream flow and sedimentation characteristics change, resulting in new and/or potentially harmful forms of chemicals affecting instream or benthic organisms.

The following discussion provides examples of impacts that may be present as a result of different kinds of channelization. For a more detailed discussion of types of channelization projects and potential impacts, see Watson et al. (1999).

Straightening

Channels are straightened for a multitude of reasons, such as directing water away from a particular structure or area and to reduce local flooding. Channelization that involves straightening of the stream channel increases the slope of the channel, which results in higher discharge velocities. Impacts associated with increased water velocities include more streambank and streambed erosion, higher sediment loads, and increased transport of nutrients and other pollutants (FISRWG, 1998).

An increase in the sediment load could lead to increased turbidity, which then may cause an increase in stream temperature because the darker sediment particles absorb heat (USEPA, 1997b). Changes in water temperature can influence several abiotic chemical processes, such as dissolved oxygen concentrations, sorption of chemicals onto particles, and volatilization rates. Water temperature influences reareation rates of oxygen from the atmosphere. Dissolved oxygen concentrations in water are inversely related to temperature; solubility of oxygen decreases with increasing water temperature. In addition, sorption of chemicals to particulate matter and volatilization rates are influenced by changes in water temperature. Sorption often decreases with increasing temperature and volatilization increases with increasing temperature (University of Texas, 1998).

An increased sediment load that contains significant organic matter can increase the sediment oxygen demand (SOD). The SOD is the total of all biological and chemical processes in sediment that consume oxygen (USEPA, 2003a). These processes occur at or just below the sediment-water interface. Most of the SOD at the surface of the sediment is due to the biological decomposition of organic material and the bacterially facilitated nitrification of ammonia, while the SOD several centimeters into the sediment is often dominated by the chemical oxidation of species such as iron, manganese, and sulfide (Wang, 1980; Walker and Snodgrass, 1986 from USGS, 1997). Increases in SOD can lead to lower levels of dissolved oxygen, which can be harmful to aquatic life.

Lining

The sides of channels can be lined with materials such as metal sheeting, concrete, wood, or stone to prevent erosion of a particular section of stream channel or stream bank. The artificially lined areas can reduce the friction between the channel and flowing water, leading to an increase in velocity. The increased velocity and thus the increased erosive potential of the flowing water are not able to erode the artificially lined channel area and can result in augmented erosion downstream as well as increased downstream flooding (Brookes, 1998). Lining the channel also removes aquatic habitat and important substrates that are essential to aquatic life.

Narrowing

Narrowing of a stream channel often occurs when flood control measures such as levees and floodwalls are implemented. By narrowing a stream channel, the water is forced to flow through a more confined area and thus travels at an increased velocity. The increased velocity in turn increases the stream’s erosive potential and ability to transport sediment. This can lead to increased erosion of the streambank and shoreline in downstream locations.

When a channel is made narrower, the water depth increases and the surface area exposed to the solar radiation and ambient temperature decreases, especially in the warmer months. This can cause a decrease in the water temperature. Increased depth may also reduce the surface area of the water in contact with the atmosphere and affect the transfer of oxygen into the water.

Widening

Channel widening is often performed to increase a channel's ability to transport a larger volume of water. The design is often geared to volumes of water that occur during flood events. The design of a channel modification project to increase the channel's ability to transport a large volume of water will determine the characteristic of the water flow. The widening of a channel can result in a channel with a capacity to transport water that far exceeds the typical daily discharge. This results in a typical flow that is shallow and wide. As a result of increased contact with the streambed and streambank, there is increased friction and a decreased water velocity. The decrease in velocity causes sediment to settle out of the water column and accumulate within the stream channel. This accumulation of sediment can decrease the capacity of the stream channel. The decreased depth and increased surface area of the water exposed to solar radiation and ambient air temperatures can lead to an increase in water temperature. A change in water temperature can influence dissolved oxygen concentrations as dissolved oxygen solubility decreases with increasing water temperature.

Where tidal flow restrictors cause impoundments, there may be a loss of streamside vegetation, disruption of riparian habitat, changes in the historic plant and animal communities, and decline in sediment quality. Restricted flows can impede the movement of fish or other aquatic life. Flow alteration can reduce the level of tidal flushing and the exchange rate for surface waters within coastal embayments, with resulting impacts on the quality of surface waters and on the rates and paths of sediment transport and deposition.

Culverts and Bridges

The presence of culverts and bridges along a channel can have an impact on the physical and chemical qualities of the water. A culvert can be in the form of an arch over a channel or a pipe that encircles a channel and it functions to direct flow below a roadway or other land use. The elimination of exposure to solar radiation while water flows through a culvert can result in a decrease in water temperature and the associated physical or chemical changes.

A culvert or the supports of a bridge can confine the width of a channel forcing the water to flow in a smaller area and thus at a higher velocity. Impacts associated with a higher flow velocity include increased erosion. An arch culvert maintains the natural integrity of the stream bottom. In addition, as compared with the natural substrate that can be found using an arch culvert without concrete inverts (floors), a pipe culvert may create less friction with the water flow and result in an increased flow velocity. The chemical and physical changes associated with increased erosion and sediment transport capacity would then result.

The culvert acts as a fixed point with a fixed elevation within the stream channel and as the stream attempts to adjust over time, the culvert remains stationary. Placement of this type of structure disturbs the natural equilibrium of a channel. A culvert acts as a grade control structure, and as such, may serve to prevent upstream migrating incision (headcutting) from moving further up the channel. Depending on the watershed processes, it may act to preserve the natural equilibrium of a channel. Alterations to a stream channel can result in local areas of instability or system wide channel instability (FISRWG, 1998). Increased erosion below and increased deposition above the structure are likely and can lead to several of the water quality impacts, such as increased SOD or changes in metal sorption rates, discussed above.

Urbanization

As humans develop watersheds, the proportions of pervious and impervious land within the watershed change. Development also changes vegetative cover into house, buildings, roads, and other non-vegetative cover. The result is a change in the fate of water from rainfall events. Generally, as imperviousness increases and vegetative cover is lost:

- Runoff increases
- Soil percolation decreases
- Evaporation decreases
- Transpiration decreases

Increased volumes of runoff resulting from some types of watershed development can result in hydraulic changes in downstream areas including bank scouring, channel modifications, and flow alterations (Anderson, 1992; Schueler, 1987). The resulting changes to the distribution, amount, and timing of flows caused by flow alterations can affect a wide variety of living resources. As urbanization occurs, changes to the natural hydrology of an area are inevitable. During urbanization, pervious spaces, including vegetated and open forested areas, are converted to land uses that usually have increased areas of impervious surface, resulting in increased runoff volumes and pollutant loadings. Hydrologic and hydraulic changes occur in response to site clearing, grading, and change in landscape. Water that previously infiltrated the ground and was slowly released now runs off quickly into stream networks. Development, with corresponding increases in imperviousness, can lead to:

- Bankfull and subbankfull floods that increase in magnitude and frequency
- Dimensions of the stream channel are no longer in equilibrium with its hydrologic regime
- Channels enlarge
- Stream channels are highly modified by human activity
- Upstream channel erosion contributes greater sediment load to the stream
- Dry weather flow to the stream declines
- Wetland perimeter of the stream declines
- In-stream habitat structure degrades
- Large woody debris is reduced
- Stream crossings and potential fish barriers increase
- Riparian forests become fragmented, narrower, and less diverse
- Water quality declines
- Summer stream temperatures increase
- Aquatic diversity is reduced

For more information on hydrologic problems associated with urbanization, refer to the *National Management Measures to Control Nonpoint Source Pollution from Urban Areas* (USEPA, 2005d).

The hydraulic changes associated with urbanization have often been addressed with solutions determined by channelization and channel modifications. Evaluating impacts from urbanization on a watershed scale and planning solutions on the same watershed scale can often prevent the transference of upstream problems to downstream locations. There are a variety of management activities that can reduce the impacts associated with urban development. When these urban impacts are reduced, additional hydromodification impacts, such as channelization and channel modification or streambank and shoreline erosion effects, may be reduced. Changes in urban development practices that result in reduced sediment in runoff can enhance reservoir quality and lessen the need for management activities to reduce NPS impacts associated with the operation of dams. For additional information on management practices that address urbanization issues, refer to USEPA, 2005d.

Agricultural Drainage

Some activities, including channelization and channel modification, that take place within a watershed, can lead to unintended adverse effects on watershed hydrology. Even when the intended effect of the watershed activity is to reduce pollution or erosion for an area within a watershed, the impact of the project to the entire watershed’s hydrology should be evaluated. Since hydrology is important to the detachment, transport, and delivery of pollutants, better understanding of these effects can lead to reduction of nonpoint source pollution problems (USEPA, 2003b).

One example of an activity that has been shown to provide localized NPS benefits, but can negatively affect the hydrology of a watershed is an agricultural drainage system. The main purpose of agricultural drainage is to provide a root environment suitable for plant growth, but it can also be used as a means of reducing erosion and improving water quality. Despite the localized positive effects of drainage, when drainage water is poor in quality or contains elevated levels of pollutants, adverse impacts may occur downstream within a watershed. Concentrations of salts, nutrients, and other crop-related chemical, such as fertilizers and pesticides can damage downstream aquatic ecosystems. Many agricultural drainage systems include drain tiles placed strategically throughout a field to create a network of gravity fed drains. The drain tiles empty into a collection pipe that drains to a waterbody nearby. With the drain system in place and operating, water will leave the affected area quicker and at one or more focused points. Water from the drainage system may erode the banks of unlined surface drains, contribute to flashier runoff events in the receiving water or downstream, and increase the load of sediment in drainage water (USEPA, 2003b).

Because of these adverse effects, drainage planners should analyze effluents from these systems for nutrients and pesticides to determine possible downstream impacts. Care should also be taken with drainage water so that it does not negatively alter the hydrology of a watershed (FAO, 1997). The degree to which management activities, such as agricultural drainage systems, affect watersheds beyond their intended purpose should be evaluated. In some cases, a thorough assessment and thoughtful discussion with key stakeholders is enough to evaluate the potential impacts of a project on hydrology. However, in many instances, some form of modeling is probably needed to integrate various small and large impacts of watershed activities. For more information on agricultural drainage and management practices related to agricultural drainage, refer to *National Management Measures for the Control of Nonpoint Pollution from Agriculture* (USEPA, 2003b).

Biological and Habitat Impacts

Changes in habitat and biological communities following hydromodification of a channel can be highly site-specific and complex. The physical and chemical alterations resulting from channelization impact various habitats and biological communities within a channel, including instream algae, fish, macroinvertebrate populations, and bank or floodplain vegetation. Mathias and Moyle (1992) compared unchannelized and channelized sections of the same stream and found a much higher diversity of many organisms, including aquatic invertebrates, fish, and riparian vegetation, in the unchannelized sections of the stream. Adams and Maughan (1986) compared the benthic community in a small headwater stream, prior to and after channelization. They found that the pathways of organic input shifted from materials associated with leaf fall and runoff to materials associated with periphyton production. Accompanying this change was a shift of the assemblage from shredder domination to grazer domination and a decrease in diversity. Biological and habitat impacts caused by channelization can result from increased stream velocity, decreases in pool and riffle habitat complex, decrease in canopy cover, increase in the solar radiation reaching the channel, channel incision, and increases in sediment.

Channelization of a stream may increase velocity due to increased channel slope and decreased friction with the bank and bed material. Changes in the velocity may cause an impact to organisms within the channel. For example, fish may have to expend more energy to stay in swifter currents and their source of food may be swept downstream. Studies have demonstrated that fisheries associated with channelized streams are far less productive that those of non-channelized streams (Jackson, 1989). Increased rates of erosion as a result of increased velocities downstream of a channelization feature can also create unstable streambanks, which could lead to higher risks of flooding and ultimately negative impacts to aquatic organisms.

Channelization can result in a more uniform stream channel that is void of the pool and riffle habitat complex or obstructions, such as woody debris inputs. As repeatedly observed, this can result in changes to the biological community. Negishi et al. (2002) observed a decrease in the total density of macroinvertebrates in the middle of a channelized stream and a decrease in taxon richness in the middle and edge of a channelized stream. An overall reduction in habitat heterogeneity is likely responsible for the reduction in species diversity and the increased abundance of those species favored by the altered flows that is typically observed (Allan, 1995). On medium-sized unregulated rivers, Benke (2001) found that habitat-specific invertebrate biomass was highest on snags, followed by the main channel and then the floodplain. It was concluded that invertebrate productivity from these habitats has likely been significantly diminished as a result of snag removal, channelization, and floodplain drainage (Benke, 2001).

The survival of the Gulf Coast walleye (*Stizostedion vitreum*) relies on the availability of appropriate spawning habitat, such as large woody debris, that locally reduce current velocity. Channelization and the removal of structures have been identified as activities of concern that could threaten the survival of the species (VanderKooy and Peterson, 1998). In one experiment, an assessment of water quality using environmental indices, such as macroinvertebrate communities, found that channelization and deforestation resulted in a completely different and less varied biocommunity (Bis, 2000). A lower persistence of the macroinvertebrate assemblage in the channelized stream was attributed to the lower availability of flow such as backwaters and inundated habitats (Negishi et al., 2002). In a study by Kubecka and Vostradovsky (1995), low fish populations were attributed to channelization of the riverbed.

The channelization of a river can also result in a decrease in canopy cover and an increase in the solar radiation reaching the channel. Bis (2000) found that an increase in incident radiation on a river resulted in increased algal productivity and a significant decrease in scrapers, a macroinverterate that feeds on periphyton or algae growing on plant surfaces (Bis, 2000). Increased water temperatures can also lead to a shift in the algal community to predominately planktonic algal communities, which disrupts the aquatic food chain (Galli, 1991). The combination of increased water temperatures and loss of riparian vegetation falling into the stream (which provides both food and cover) may be responsible for the decrease in macroinvertebrates. Increased solar radiation on a channelized stream can act to decrease productivity by reaching the level of photoinhibition; a decrease in productivity due to excessive amounts of solar radiation. The temperature of the water can also be increased to the extent that it adversely impacts organisms. Elevated temperatures disrupt aquatic organisms that have narrow temperature limits, such as trout, salmon, and aquatic insects.

Incision of a channel, a common impact of channelization, disconnects the channel from the floodplain by raising the floodplain relative to the riverbed and decreasing the occurrence of overbank flow. Channel incision or downcutting has rarely been found to directly affect the biotic ecosystem, but indirect changes in habitat conditions are significant. Channel incision decreases habitat heterogeneity and, as a result, biodiversity (Tachet, 1997). An analysis of forest overstory, understory, and herbaceous strata along a channelized and unchannelized stream showed that there was a difference in terms of size-class structure and woody debris quantity (Franklin et al., 2001). Riparian wood die back on a channel that is incised because of upstream channelization was attributed to a decrease in over bank flooding and a lowering of the water table as the stream became incised (Steiger et al., 1998). A comparison of a regulated and an unregulated river in Colorado's Green River basin found a difference in riparian vegetation composition. The regulated river supported banks with wetland species that survive in anaerobic soils and terraces with desert species adapted to xeric soil conditions. The unregulated river supported riparian vegetation that changed along a more gradual environmental continuum from a river channel to a high floodplain (Merritt and Cooper, 2000).

Sediment affects the use of water in many ways. When the rate of erosion changes, transport and deposition of sediment also changes. Excessive quantities of sediment can bury benthic organisms and the habitat of fish and waterfowl. Suspended solids in the water reduce the amount of sunlight available to aquatic plants, cover fish spawning areas and food supplies, fill rearing pools, reduce beneficial habitat structure in stream channels, smother coral reefs, clog the filtering capacity of filter feeders, and clog and harm the gills of fish. Those fish species that rely on visual means to get food may be restricted by increased turbidity. Sedimentation effects combine to reduce fish, shellfish, coral, and plant populations and decrease the overall productivity of lakes, streams, estuaries, and coastal waters.

Management Measure for Physical and Chemical Characteristics of Channelized or Modified Surface Waters

Management Measure
1) Evaluate the potential effects of proposed channelization and channel modification on the physical and chemical characteristics of surface waters. 2) Plan and design channelization and channel modification to reduce undesirable impacts. 3) Develop an operation and maintenance program for existing modified channels that includes identification and implementation of opportunities to improve physical and chemical characteristics of surface waters in those channels.

A. Introduction

This management measure is intended to occur concurrently with the implementation of the Management Measure for Instream and Riparian Habitat Restoration, which follows this management measure. It applies to any proposed channelization or channel modification projects to evaluate potential changes in surface water characteristics, as well as to existing modified channels that can be targeted for opportunities to improve the surface water characteristics necessary to support desired fish and wildlife.

The purpose of the management measure is to ensure that the planning process for new hydromodification projects addresses changes to physical and chemical characteristics of surface waters that may occur as a result of proposed work. For existing projects, this management measure can be used to ensure the operation and maintenance program uses any opportunities available to improve the physical and chemical characteristics of the surface waters.

Changes created by channelization and channel modification activities are problematic if they unexpectedly alter environmental parameters to levels outside normal or desired ranges. The physical and chemical characteristics of surface waters that may be influenced by channelization and channel modification include sedimentation, turbidity, salinity, temperature, nutrients, dissolved oxygen, oxygen demand, and contaminants. Changes in natural sediment supplies, reduced freshwater availability, and accelerated delivery of pollutants are examples of the types of changes that can be associated with channelization and channel modification.

Published case studies of existing channelization and channel modification projects describe alterations to physical and chemical characteristics of surface waters (Shields et al., 1995; Burch et al., 1984; Petersen, 1990; Reiser et al., 1985; Roy and Messier, 1989; Sandheinrich and Atchison, 1986; Sherwood et al., 1990). Frequently, the post-project conditions are intolerable to desirable fish and wildlife. The literature also describes instream benefits for fish and wildlife that can result from careful planning of channelization and channel modification projects

(Bowie, 1981; Los Angeles River Watershed, 1973; Sandheinrich and Atchison, 1986; Shields et al., 1990; Swanson et al., 1987; USACE, 1989).

Case Study: Rio Blanco Restoration

The Rio Blanco, a 30-mile long tributary to the San Juan River, originates at the Continental Divide in Archuleta County, Colorado. Elevation ranges from more than 13,000 ft to around 6,400 ft at the confluence with the San Juan River. In the 1950s, Congress appropriated funding to construct the San Juan–Chama Diversion Tunnel, which took water from the Rio Blanco under the Continental Divide into the Rio Grande Basin for use in New Mexico. The system began operation in 1971 and diverted approximately 70 percent of the in-stream flow of the Blanco. A basin summary prepared in 1990 by the U.S. Forest Service found that: fish habitat was poor; sediment loads were high because of flow changes and streambank erosion; sediment supply was greater than stream transport capacity; water temperatures were high; and diversion and land use practices created a wide, shallow stream with little pool and cover habitat.

In 1997 the San Juan Water Conservancy District and Colorado Water Conservation Board initiated a demonstration project under Colorado's Nonpoint Source Management Program for hydromodification. A total of $96,000 of 1997 section 319 funds were used in the demonstration. Matching funds totaling more than the required $64,000 were provided by contributions from a variety of organizations, associations, conservation districts, and local landowners. The goal of the project was to improve stream water quality and aquatic habitat by reducing low-flow water temperatures and reducing sediment loading. These goals were achieved by (1) narrowing and deepening the channel and creating overhead and in-stream cover and by (2) stabilizing banks and enhancing sediment transport capacity through increasing the stream width/depth ratios.

The project overcame considerable opposition from some adjacent landowners, who feared construction would adversely affect the water level in their alluvial wells. The project was finally constructed in fall 1999 over 1.1 miles of the river below the San Juan/Chama diversion. Some of the early observations include the following:

- Pools in the river are now nearly 7 feet deep; previously, they were nonexistent or less than 2 feet deep.
- The channel is well defined and meanders, instead of braiding through the width of the riverbed.
- Water levels in alluvial wells have increased by 7 to 10 inches.
- Within a week of completing construction, children caught 10- to 16-inch fish in this river segment.
- Water temperatures have dropped by almost 3 degrees according to preliminary studies.

The second phase of the project was announced by the San Juan Water Conservation District almost four years after the initial demonstration project. State and local entities combined funds to reach the necessary $167,000 to match a US EPA section 319 fund of $250,000. This phase extends approximately 1.5 miles downstream. As a heavily populated area, the restoration required the permission of 72 properties, each of which complied. Once this segment is completed, a total of almost three miles will be restored. While a completion date for the remainder of the downstream segment extending to the juncture with the San Juan River is unknown, it takes approximately two years to obtain grant funding once an application has been submitted and the funds must be utilized within five years. It is estimated that restoring the remainder of the downstream segment will cost in excess of one million dollars. Due to the high cost of the restoration and the limited funding, it is likely that the downstream sections will continue to be restored in segments.

Sources:

Colorado NPS Connection.2001. *The Death and Rebirth of the Rio Blanco*. http://ourwater.org/connection/con.3forweb.pdf. Accessed July 2003.

San Water Conservancy District. *Rio Blanco Project*. http://www.waterinfo.org/rioblanco.html. Accessed July 2003.

Sluis, T. November 16, 2000. New Rio Blanco: Habitat restoration project narrows and deepens river. *The Durango Herald*. http://cwcb.state.co.us/isf/programs/RioBlancoArticle.htm. Accessed July 2003.

USEPA. 2002. *Rio Blanco Restoration: Adopted Rocks and Homemade Jelly Help Fund Demonstration Project*. U.S Environmental Protection Agency, Section 319 Success Stories. http://www.epa.gov/owow/nps/Section319III/CO.htm. Accessed June 2003.

Implementation of this management measure should begin during the planning process for new projects. For existing projects, implementation of this management measure can be included as part of a regular operation and maintenance program. The approach is two-pronged and should include:

1. *Planning and evaluation*, with numerical models for some situations, of the types of NPS pollution related to instream changes and watershed development.
2. *Operation and maintenance programs that apply* a combination of nonstructural and structural practices to address some types of NPS problems stemming from instream changes or watershed development.

B. Practices for Planning and Evaluation

Use models/methodologies as one means to evaluate the effects of proposed channelization and channel modification projects on the physical and chemical characteristics of surface waters. Evaluate these effects as part of watershed plans, land use plans, and new development plans.

Physical and chemical effects of hydraulic and hydrologic changes to streams, rivers, or other surface water systems can be estimated with models and past experience in situations similar to those described in the case studies discussed in this chapter. These models can simulate many of the complex physical, chemical, and biological interactions that occur when hydraulic changes are imposed on surface water systems. Additionally, models can be used to determine a combination of practices to mitigate the unavoidable effects that occur even when a project is properly planned. Models, however, cannot be used independently of expert judgment gained through past experience. When properly applied models are used in conjunction with expert judgment, the effects of channelization and channel modification projects (both potential and existing projects) can be evaluated and many undesirable effects prevented or eliminated.

In planning-level evaluations of proposed hydromodification projects, it is critical to understand that the surface water quality and ecological impact of the proposed project will be driven primarily by the alteration of physical transport processes. In addition, it is critical to realize that the most important environmental consequences of many hydromodification projects will occur over a long-term time scale of years to decades.

Off the coast of eastern Long Island, Shinnecock Canal connects Peconic Bay with Shinnecock Bay. The canal has a tide gate that operates to allow water to flow only from Shinnecock Bay into Peconic Bay and closes when the tide height in Peconic Bay is higher than Shinnecock Bay. A 3-D EFDC model was used to simulate the tide gate opening and closing. This enables planners to study the effects of the tide gate on water quality in the bays.

The key element in the selection and application of models for the evaluation of the environmental consequences of hydromodification projects is the use of appropriate models to adequately characterize circulation and physical transport processes. Appropriate surface water quality and ecosystem models (e.g., salinity, sediment, cultural eutrophication, oxygen, bacteria, fisheries, etc.) are then selected for linkage with the transport model to evaluate the environmental impact of the proposed hydromodification project. There are several sophisticated two-dimensional (2D) and three-dimensional (3D) time-variable hydrodynamic models available for environmental assessments of hydromodification projects. Two-dimensional depth or laterally averaged hydrodynamic models can be routinely applied to assist with environmental assessments of beneficial and adverse effects on surface water quality by knowledgeable teams of physical scientists and engineers (Hamilton, 1990). Three-dimensional hydrodynamic models are also beginning to be more widely applied for large-scale environmental assessments of aquatic ecosystems (e.g., EPA/USACE-WES Chesapeake Bay 3D hydrodynamic and surface water quality model).

In the USACE's report, *Review of Watershed Water Quality Models* (Deliman et al., 1999), the authors compare and evaluate existing hydrologic and watershed water quality models, make recommendations for base model(s) for predicting NPS pollution, and identify areas for model improvement. The authors review commonly used and well validated models used in urban or nonurban settings. Users of the models can use the report to obtain basic model information and to review how well the models simulate nonpoint source pollution and where the authors think improvements could be made. This information might be useful to readers who are trying to select the best model for analyzing how to reduce nonpoint source pollution in their watershed (Deliman et al., 1999). The report is available for review at http://el.erdc.usace.army.mil/elpubs/pdf/trw99-1.pdf.

Table 1.1 lists some of the available models for studying the effects of channelization and channel modification activities.

Table 1.1 Models Applicable to Hydromodification Activities

Model	Dimension	Description	Source and Contact*
WASP	1, 2, or 3	Water Quality Analysis Simulation Program. Framework for modeling contaminant fate and transport in surface waters. The WASP framework can be used to model biochemical oxygen demand and dissolved oxygen dynamics, nutrients and eutrophication, bacterial contamination, and organic chemical and heavy metal contamination.	EPA, Environmental Research Laboratory, Athens, Georgia, 1996. Model Distribution Coordinator, U.S. EPA, Center for Exposure Assessment Modeling 960 College Station Road Athens, GA 30605 http://www.epa.gov/ceampubl/swater/wasp/index.htm
SMS (RMA2 and RMA4)	1, 2	The Surface-Water Modeling System is a generalized numerical modeling system for open-channel flows, sedimentation, and constituent transport.	USACE. U.S. Army Waterways Experiment Station Hydraulics Laboratory, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=Software;4
TABS-MD (RMA2, RMA4, RMA10, SED2D)	1, 2, or 3	The multi dimensional numerical modeling system is a collection of generalized computer programs and utility codes, designed for studying multidimensional hydrodynamics in rivers, reservoirs, bays, and estuaries. The models can be applied to study project impacts of flows, sedimentation, constituent transport, and salinity.	USACE. U.S. Army Waterways Experiment Station Hydraulics Laboratory, Coastal and Hydraulics laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=Software;10
HEC-6	1	HEC-6 is a one dimensional moveable boundary open channel flow numeric model designed to simulate and predict changes in river profiles resulting from scour and deposition over moderate time periods, typically years. Latest revision occurred in 1993.	USACE. Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616 http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm

Model	Dimension	Description	Source and Contact*
SAM	1	The model calculates the width, depth, slope and n-values for stable channels in alluvial material. SAM can be used to evaluate erosion, entrainment, transportation, and deposition in alluvial streams. Channel stability can be evaluated, and the evaluation used to determine the cost of maintaining a constructed project. The model is currently being improved and enhanced at WES.	USACE. U.S. Army Waterways Experiment Station Hydraulics Laboratory, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180 http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=Software;2
HEC-RAS	1	HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. The model allows you to perform one-dimensional steady flow, unsteady flow, and sediment transport calculations. The key element is that all three components will use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. The HEC-RAS modeling system was developed as a part of the Hydrologic Engineering Center's "Next Generation" (NexGen) of hydrologic engineering software. The NexGen project encompasses several aspects of hydrologic engineering, including: rainfall-runoff analysis; river hydraulics; reservoir system simulation; flood damage analysis; and real-time river forecasting for reservoir operations.	USACE. Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616 http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html Additional information: http://el.erdc.usace.army.mil/elpubs/pdf/smartnote04-2.pdf

Model	Dimension	Description	Source and Contact*
HEC-HMS	1	The HEC-HMS model is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is applicable in a wide range of geographic areas for solving the widest possible range of problems, including large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.	USACE. Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616 http://www.hec.usace.army.mil/software/hec-hms/hechms-hechms.html Additional information: http://el.erdc.usace.army.mil/elpubs/pdf/smartnote04-3.pdf
CH3D-SED	1, 2, or 3	The CH3D numerical modeling system can be used to investigate sedimentation on bendways, crossings, and distributaries. Applications address dredging, channel evolution, and channel training structure evaluations.	USACE. U.S. Army Waterways Experiment Station Hydraulics Laboratory, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://chl.wes.army.mil/software/ch3d/
CE-QUAL-RIV1	1	CE-QUAL-RIV1 is a one-dimensional (cross-sectionally averaged) hydrodynamic and water quality model, meaning that the model resolves longitudinal variations in hydraulic and quality characteristics and is applicable where lateral and vertical variations are small. CE-QUAL-RIV1 consists of two parts, a hydrodynamic code (RIV1H) and a water quality code (RIV1Q). The hydrodynamic code is applied first to predict water transport and its results are written to a file, which is then read by the quality model. It can be used to predict one-dimensional hydraulic and water quality variations in streams and rivers with highly unsteady flows, although it can also be used for prediction under steady flow conditions.	USACE. U.S. Army Waterways Experiment Station Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://www.wes.army.mil/el/elmodels/riv1info.html

Model	Dimension	Description	Source and Contact*
HIVEL2D	1, 2	HIVEL2D is a free-surface, depth averaged model designed specifically to simulate flow in typical high-velocity channels.	Developed by USACE. U.S. Army Waterways Experiment Station Hydraulics Laboratory, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=Software;6
EFM	1	Ecosystem Functions Model (EFM) is a planning tool that analyzes ecosystem response to changes in flow regime. EFM allows environmental planners, biologists, and engineers to determine whether proposed alternatives (e.g., reservoir operations, levee alignments) would maintain, enhance, or diminish ecosystem health. Project teams can use EFM software to visualize existing ecologic conditions, highlight promising restoration sites, and assess and rank alternatives according to the relative enhancement (or decline) of ecosystem aspects. The hydraulic modeling portion of the EFM process is performed by existing independent software, such as HEC-RAS.	USACE. U.S. Army Engineer Research and Development Center, ATTN: CEERD-EP-P, 3909 Halls Ferry Road, Vicksburg, MS 39180. http://el.erdc.usace.army.mil/elpubs/pdf/smartnote04-4.pdf
EFDC	1, 2, or 3	Environmental Fluid Dynamics Code. This is a single source 3D finite-difference modeling system having hydrodynamic, water quality-eutrophication, sediment transport and toxic contaminant transport components linked together.	John Hamrick developed this at the Virginia Institute of Marine Science 1990-1991. Dr. John Hamrick, Tetra Tech, Inc. 10306 Eaton Place, Suite 340 Fairfax, VA 22030
FESWMS-2DH	2	FESWMS-2DH is a finite element surface water modeling system for two-dimensional flow in a horizontal plane. The model can simulate steady and unsteady surface water flow and is useful for simulating two-dimensional flow where complicated hydraulic conditions exist (e.g., highway crossings of streams and flood rivers). It can also be applied to many types of steady or unsteady flow problems. (Last updated: 1995)	U.S. Geological Survey, Hydrologic Analysis Software Support Program, 437 National Center, Reston, VA 20192. http://water.usgs.gov/cgi-bin/man_wrdapp?feswms-2dh

Model	Dimension	Description	Source and Contact*
BRANCH	1	The Branch-Network Dynamic Flow Model is used to simulate steady state flow in a single open channel reach or throughout a system of branches connected in a dendritic or looped pattern. The model is typically applied to assess flow and transport in upland rivers where flows are highly regulated or backwater effects are evident, or in coastal networks of open channels where flow and transport are governed by the interaction of freshwater inflows, tidal action and meteorological conditions. (Last updated: 1997)	U.S. Geological Survey, Hydrologic Analysis Software Support Program, 437 National Center, Reston, VA 20192. http://water.usgs.gov/cgi-bin/man_wrdapp?branch
RiverWare™	1	RiverWare™ is a reservoir and river modeling software decision support tool. With RiverWare™, users can model the topology, physical processes and operating policies of river and reservoir systems, and make better decisions about how to operate these systems by understanding and evaluating the trade-offs among the various management objectives. Water management professionals can improve their management of river and reservoir systems by using the software. The Bureau of Reclamation, the Tennessee Valley Authority, and the Army Corps of Engineers sponsor ongoing RiverWare™ research and development.	Source: Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES), http://cadswes.colorado.edu/riverware/
SIAM	N/A	SIAM is a model designed to simulate the movement of sediment through a drainage network from source to outlet. It allows for evaluation of numerous sediment management alternatives relatively quickly. The model provides an intermediate level of analysis more quantitative than a conventional geomorphic evaluation, but less specific than a numerical, mobile-boundary simulation. SIAM is to be incorporated into a future release of HEC-RAS, and is currently undergoing Beta testing. [to update when model is final]	USDOI, Bureau of Reclamation, Technical Service Center, 6th and Kipling, Denver, Colorado 80225, http://www.usbr.gov/pmts/sediment/model/siam/index.html Additional information: http://www.wes.army.mil/rsm/pubs/pdfs/RSM-2-WS04.pdf

* Note: USACE = U.S. Army Corps of Engineers

Listed below are examples of channelization and channel modification activities and associated models that can be used in the planning process.

Impoundments

A low-complexity option for modeling impoundments is to use simple models like the Bathtub model to simulate the waterbody. Compared to more complex multi-dimensional models, which use multiple computational cells to estimate volumetric and contaminant fluxes between the cells, Bathtub-type models typically use a single cell. This single cell, while a simplification of the system, may be appropriate if the system is fully mixed in both the horizontal and vertical dimensions. This approach can also be economically developed using spreadsheets (such as Excel) to calculate the results. However, a Bathtub-type model has limited utility if the water body is stratified or if results are required at more than one location in the system.

Another example of a modeling tool that has the ability to simulate impoundments is CE-QUAL-W2, a two-dimensional hydrodynamic water quality model. CE-QUAL-W2 provides results for either a horizontal or cross-sectional two-dimensional plane. Because the model assumes a vertically or horizontally-mixed environment, it is best suited for relatively long and narrow water bodies (rivers, lakes, reservoirs, and estuaries) that exhibit longitudinal or vertical water quality stratification. The water quality portion of CE-QUAL-W2 includes the major processes of eutrophication kinetics and a single algal compartment. The bottom sediment compartment stores settled particles, releases nutrients to the water column, and exerts sediment oxygen demand based on user-supplied fluxes; a full sediment diagenesis (i.e., the process of chemical and physical change in deposited sediment during its conversion to rock) model is under development.

The Environmental Fluid Dynamics Code (EFDC) is a general-purpose modeling package for simulating one- or multi-dimensional flow, transport, and bio-geochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. The EFDC model was originally developed by Hamrick in 1992 at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software. This model is now EPA-supported as a component of EPA Region 2's PRVI BASINS software system and EPA's TMDL Toolbox (http://www.epa.gov/athens/wwqtsc/html/efdc.html), and has been used extensively to support TMDL development throughout the country. In addition to hydrodynamic, salinity, and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and non-cohesive sediment transport, near field and far field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. Figure 1.2 provides an example of a post-processing analysis of EFDC model results.

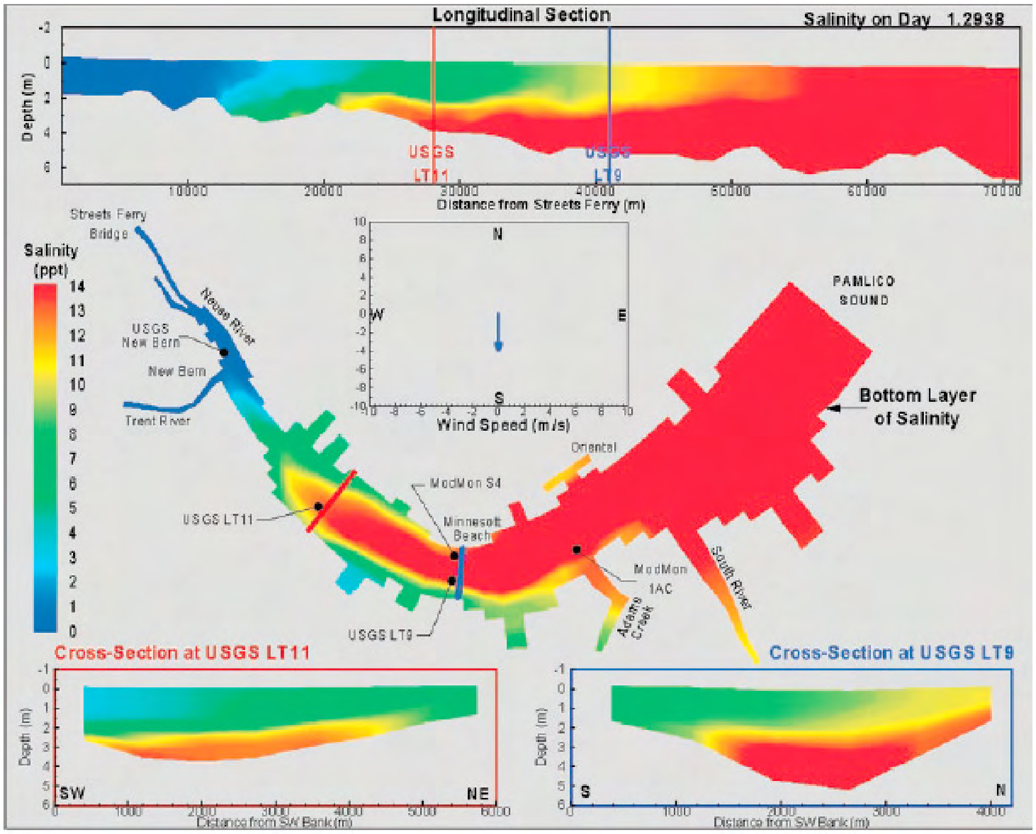


Figure 1.2 Post-processing Analysis of EFDC Model Results. Note the Horizontal and Vertical Plotting Capabilities

Estuary Tidal Flow Restrictions

Artificial hydraulic structures have the ability to alter the natural flow patterns (hydrodynamic) in an estuary, which in turn may modify erosion patterns, salinity regimes, and the fate and transport of pollutants. Some examples of artificial hydraulic structures include culverts, bridges, tide gates, and weir structures. Installation or removal of these structures may cause a significant change in local hydrodynamics, and tools may be used to estimate the impacts prior to the modification.

The EFDC model, as described above, allows modelers to evaluate the impacts of hydraulic structures, such as culverts, bridges, tide gates, and weirs. Due to the flexibility of EFDC, each of these structures can also be conceptually represented in a variety of ways. For example, the weir equation can be applied to locations in the modeling grid to estimate water surface-dependent flow through one or more grid cells. This enables a modeler to evaluate the effect of placement of structures that modify surface flow patterns (such as a weir). Structures such as piers and impermeable barriers (e.g jetties, breakwaters) can also be simulated using this code.

Another modeling tool that can address estuary tidal flow restrictions is the Finite Element Surface Water Modeling System (FESWMS) model. This modeling code was developed by the Federal Highway Administration (FHA) and is distributed by the U.S Geological Survey

(USGS). FESWMS is a hydrodynamic modeling code that simulates two-dimensional, depth-integrated, steady or unsteady surface-water flows. It supports both super and subcritical flow analysis, and area wetting and drying. FESWMS is also suited for modeling regions involving flow control structures, such as are encountered at the intersection of roadways and waterways. Specifically, the FESWMS model allows the user to include weirs, culverts, drop inlets, and bridge piers into a standard two-dimensional finite element model. FESWMS does not have three-dimensional capabilities.

Estuary Flow Regime Alterations

A number of structures or processes can alter the flow regime of a system. Flow contributions to an estuary can be altered by upstream rediversions or basin transfers, dams and dam releases, or other channel modifications. For example, when freshwater flows patterns are altered by the presence and operation of a dam, EFDC can be used to model the impact to downstream estuaries. EFDC can provide modelers with a time series representation of flow that is withdrawn from a simulated reservoir/dam system. Coupling the time series flow projections with hydrodynamic analysis of the receiving esturay enables modelers to determine potential impacts of altered flow pattems and to evaluate various spill options for the dam operation. Structures within the estuary that may alter the flow patterns include marinas, piers, jetties, and other similar type structures. Flow regime alterations due to these structures can be simulated using the same modeling tools described in the Flow Restrictions section above. Flow restrictions are the cause of most changes in the flow regime, so the simulation of the causes of restriction using a process-based modeling tool produces the desired flow alterations. Therefore, EFDC and FESWMS can be utilized in the same manner to obtain flow regime results.

Selecting Appropriate Models

Although a wide range of adequate hydrodynamic and surface water quality models are available, the central issue in selecting appropriate models for evaluating hydromodification projects is the appropriate match of the financial and geographical scale of the proposed project with the cost required to perform a credible technical evaluation of the projected environmental impact. It is highly unlikely, for example, that a proposal for a relatively small stream channel modification project, such as installing culverts in a stream segment, would be expected or required to contain a state-of-the-art hydrodynamic and surface water quality analysis that requires one or more person-years of effort. In such projects, a simplified, desktop approach (e.g., HEC-RAS Model, Figure 1.3) requiring less time and money would most likely be sufficient (USACE, 2002a). In contrast, substantial technical assessment of the

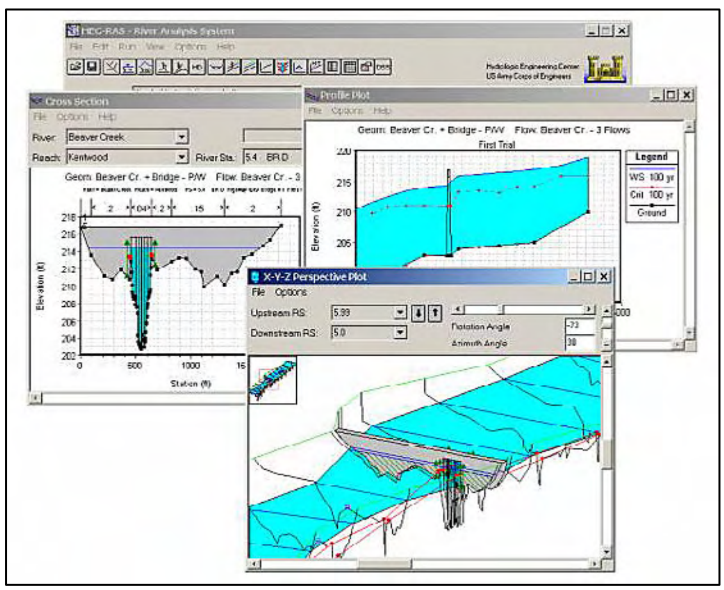


Figure 1.3 Example HEC-RAS Model Screens (Source: http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html)

long-term environmental impacts would be expected for channelization proposed as part of construction of a major harbor facility or as part of a system of navigation and flood control locks and dams. The assessment should incorporate the use of detailed 2D or 3D hydrodynamic models coupled with sediment transport and surface water quality models. Figures 1.4 and 1.5 shows screen captures of example models.

In general, six criteria can be used to review available models for potential application in a given hydromodification project:

1. Time and resources available for model application
2. Ease of application
3. Availability of documentation
4. Applicability of modeled processes and constituents to project objectives and concerns
5. Hydrodynamic modeling capabilities
6. Demonstrated applicability to size and type of project

The Center for Exposure Assessment Modeling (CEAM) (http://www.epa.gov/ceampubl), EPA Environmental Research Laboratory, Athens, Georgia, provides continual support for several hydrodynamic and surface water quality models, such as HSCTM2D, HSPF, PRZM3, and SED3D. Another source of information and technical support is the Waterways Experiment Station, U.S. Army Corps of Engineers (USACE), Vicksburg, Mississippi (http://www.wes.army.mil/). Although a number of available models are in the public domain, costs associated with setting up and operating these models may exceed the project's available resources. For a simple to moderately difficult application, the approximate level of effort varies, but could range from 1 to 12 person-months.

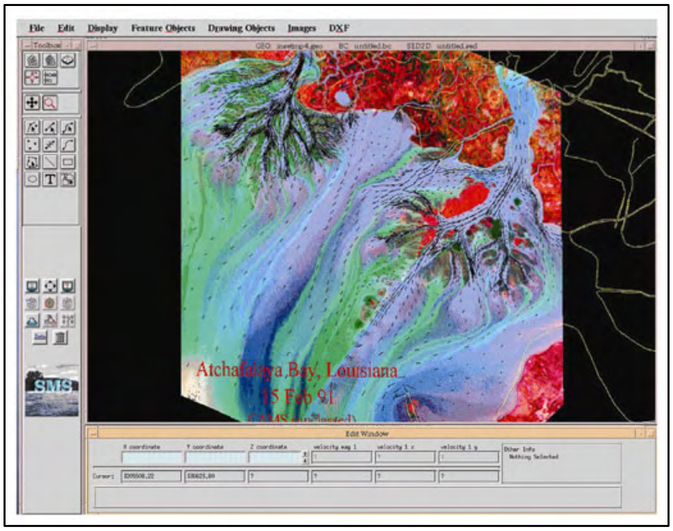


Figure 1.4 Example SMS Model Screen (Source: http://chl.erdc.usace.army.mil/Media/3/9/7/SMS8-Fact%20Sheet.pdf)

Several factors need to be considered in the application of mathematical models to predict impacts from hydromodification projects including:

- Variations and uncertainties in the accuracy of these models when they are applied to the short- and long-term response of natural systems.
- Availability of relevant information (data collection) to derive the simulations and validate the modeling results.

The cost of a given modeling project depends on a number of factors. Questions need to be asked prior to the start of a modeling project to determine the purpose and future use of the model, and/or its results. For example, the modeler needs to know if the model results are to be used deterministically (the model assumes there is only one possible result that is known for each alternative course or action), or if the model is to be used for a heuristic (involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods) scoping exercise to identify data gaps in a system. In a deterministic study, the results are traditionally compared to observed data in an effort regarded as calibration and validation. The model must therefore be rigorous enough to represent the system accurately. The complexity of the system under study is also a consideration that must be made prior to the project. The complexity of the system generally correlates well with the level of complexity of the model required to simulate it. Likewise, the more complex the model is, the more intensive it is to develop and run, and the more costly the modeling project is.

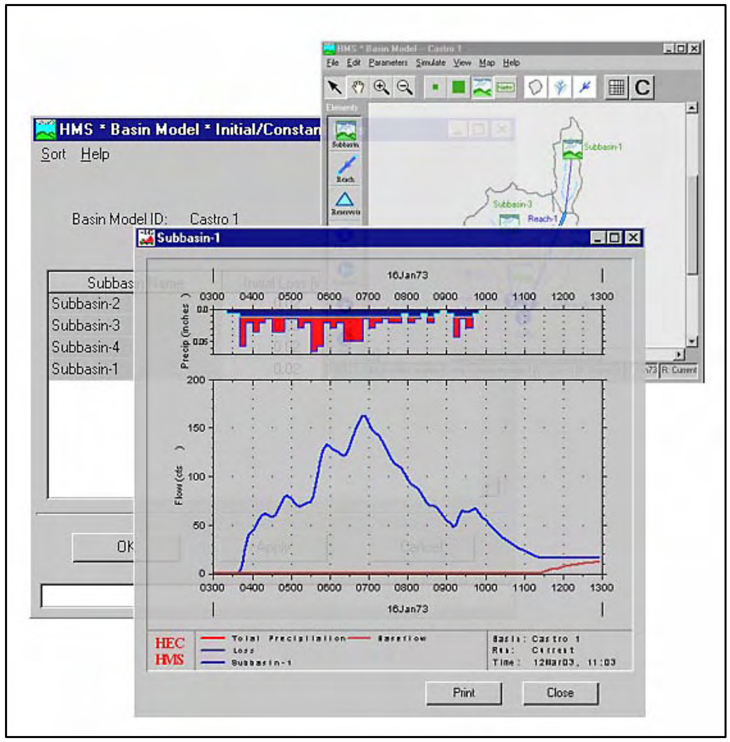


Figure 1.5 Example HEC-HMS Model Screens (Source: http://www.hec.usace.army.mil/software/hec-hms/hechms-hechms.html)

A number of approaches are available to model a given system, and the discussion above only highlights a few of the modeling tools currently available. The cost to set up a model for a given system varies tremendously, based not only on the modeling code selected, but also on what the modeler decides to simulate. For example, a modeler may aim to obtain flow results for an estuary using a given model. In reality, surface winds in that estuary may or may not be influencing the flow regime. If observed wind data is available from a weather station nearby, the modeler may choose to incorporate these data into the model to better represent that influence. The modeler may also choose not to incorporate these data, or the data may not be available. Although the modeler is utilizing the same modeling code, the decision regarding whether or not to simulate the wind conditions is not only a question regarding the model's purpose, but also what the development of this model will cost.

Modeling tools can range from simple spreadsheet tools using "back of the envelope" type calculations, to complex processed based models that must be run on high performance computing systems. As discussed previously, the tool selected for a given modeling project needs to be chosen with a number of questions in mind. As a result, each system can be modeled in a number of different ways with a number of different modeling codes. Therefore, the range in cost for even a single estuary or impoundment may range tenfold depending on the model's purpose. Typically, the cost of developing a model may range from a few thousand dollars for a simple spreadsheet model, to in excess of one million dollars for a more robust modeling system.

C. Practices for Operation and Maintenance Programs

Several management practices can be implemented to avoid or mitigate the physical and chemical impacts generated by hydromodification projects. Many of these practices have been engineered and used for several decades, not only to mitigate human-induced impacts but also to rehabilitate hydrologic systems degraded by natural processes.

In cases where existing channelization or channel modification projects can be changed to enhance instream or streamside characteristics, several practices can be included as a part of regular operation and maintenance programs. New channelization and channel modification projects that cause unavoidable physical or chemical changes in surface waters can also use one or more practices to mitigate the undesirable changes. The practices include:

- Streambank protection
- Levees
- Setback levees and floodwalls
- Grade control structures
- Vegetative cover
- Instream sediment load controls
- Noneroding roadways

By using one or more of these practices in combination with predictive modeling, the adverse impacts of channelization and channel modification projects can be evaluated, avoided, and for projects currently in place, possibly corrected.

Choosing the best practice(s) to avoid or mitigate the physical and chemical impacts generated by hydromodification projects can be difficult. The effectiveness of most practices can be influenced by a variety of site-specific factors, including upstream conditions, the extent of the bank erosion, soil type, slope, or ground cover.

Additional information about these practices, their effectiveness, limitations, and cost estimates are available from a number of sources, including:

- EPA's *National Menu of Best Management Practices for Storm Water Phase II* (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/menu.cfm)
- EPA's *Development Document for Proposed Effluent Guidelines and Standards for the Construction and Development Category* EPA-821-R-02-007 (2002), (http://www.epa.gov/waterscience/guide/construction/devdoc.htm)
- The Stormwater Manager's Resource Center (http://www.stormwatercenter.net)
- National Association of Home Builders (NAHB). 1995. *Storm Water Runoff & Nonpoint Source Pollution Control Guide for Builders and Developers*. National Association of Home Builders, Washington, DC. (http://www.nahbrc.org)

- National Stormwater Best Management Practices (BMPs) Database, sponsored by the American Society of Civil Engineers (ASCE) and the U.S. Environmental Protection Agency (EPA) (http://www.bmpdatabase.org/)
- Oregon Association of Conservation Districts, Oregon Small Acreage Fact Sheets: *Protecting Streambanks from Erosion: Tips for Small Acreages in Oregon* (http://www.or.nrcs.usda.gov/news/factsheets/fs4.pdf)
- *Urban Storm Drainage Criteria Manual: Volume 3 – Best Management Practices*. Urban Drainage and Flood Control District, Denver, CO, 1999. (http://www.udfcd.org)
- The Federal Interagency Stream Restoration Working Group. 1998. *Stream Corridor Restoration: Principles, Processes, and Practices*. (http://www.nrcs.usda.gov/technical/stream_restoration)
- U.S. Army Corps of Engineers Waterways Experiment Station (http://www.wes.army.mil)

The USDA Forest Service has published *A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization*, which provides information on how to successfully plan and implement a soil bioengineering project, including the application of soil bioengineering techniques. The guide also provides specific tips for using soil bioengineering techniques successfully and is available at: http://www.fs.fed.us/publications/soil-bio-guide. In addition, the U.S. Army Corps of Engineers has published *Bioengineering for Streambank Erosion Control*. The report, which is available at http://el.erdc.usace.army.mil/elpubs/pdf/trel97-8.pdf, synthesizes information related to bioengineering applications and provides preliminary planning and design guidelines for use of bioengineering techniques on eroded streambanks (Allen and Leech, 1997). The USACE handbook *Stream Management* (Fischenich and Allen, 2000) introduces considerations in addressing stream instabilities and presents an overview of techniques that might be considered for erosion control projects.

Additional information about hydromodification, soil bioengineering, and restoration is available from the following:

- *Ann Riley, Urban Stream Restoration: A Video Tour of Ecological Restoration Techniques* (http://www.noltemedia.com/nm/urbanstream): This video, which can be ordered online, is a documentary tour of six urban stream restoration sites. It provides background information on funding, community involvement, and the history and principles of restoration. The demonstration includes examples of stream restoration in very urbanized areas, re-creating stream shapes and meanders, creek daylighting, soil bioengineering, and ecological flood control projects. Ann Riley, a nationally known hydrologist, stream restoration professional, and executive director of the Waterways Restoration Institute in Berkley, California, leads the tour.

- *California Forest Stewardship Program*. Bioengineering to Control Streambank Erosion (http://ceres.ca.gov/foreststeward/html/bioengineering.html): This fact sheet discusses various bioengineering techniques applicable to California streams.

- *Lower American River Corridor River Management Plan* (http://www.safca.com): The plan includes aquatic habitat management goals, including restoration to improve aquatic habitat impaired by low flows from channel modification of the Lower American River.

- *Natural Resources Conservation Service, Watershed Technology Electronic Catalog* (http://www.wcc.nrcs.usda.gov/wtec/wtec.html): This online catalog is a source of technical guidance on a variety of restoration techniques and management practices, to provide direction for watershed managers and restoration practitioners. The site is focused on providing images and conceptual diagrams.

- *North Delta Improvements Project* (http://ndelta.water.ca.gov/index.html): The (NDIP), which is under the California Department of Water Resources, presents unique opportunities for synergy in achieving flood control and ecosystem restoration goals.

- *Ohio Department of Natural Resources*. Stream Management Guide Fact Sheets (http://www.dnr.state.oh.us/water/pubs/fs_st/streamfs.htm): This is a compilation of fact sheets on technical guidance for streambank and instream practices, general stream management, and stream processes.

- *Sacramento River Riparian Habitat Program* (http://www.sacramentoriver.ca.gov): The Sacramento River Riparian Habitat Program is working to ensure that riparian habitat management along the river addresses the dynamics of the riparian ecosystem and the reality of the local agricultural economy.

- *South Delta Improvement Project* (http://sdelta.water.ca.gov): The purpose of the South Delta Improvements Program (SDIP) is to incrementally maximize diversion capability into Clifton Court Forebay, while providing an adequate water supply for diverters within the South Delta Water Agency, and reducing the effects of State Water Project exports on both aquatic resources and direct losses of fish in the South Delta.

- *South Sacramento County Streams Project* (http://www.spk.usace.army.mil): South Sacramento County Streams Project provides flood damage reduction to the urban areas of the Morrison Creek and Beach Stone Lake drainage basins in the southern area of Sacramento, as well as around the Sacramento Regional Waste Water Treatment Plant. The project will fund stream restoration in southern Sacramento County.

- *USDA Natural Resources Conservation Service, Stream Visual Assessment Protocol* (http://www.nrcs.usda.gov/technical/ECS/aquatic/svapfnl.pdf): Outlines methods for field conservationists and landowners to evaluate stream ecological conditions.

- *Washington State Department of Transportation, Soil Bioengineering Web site* (http://www.wsdot.wa.gov/eesc/design/roadside/sb.htm): This is a comprehensive Web site, with information on cost, specifications, funding, and case studies.

- *WATERSHEDSS:Water, Soil and Hydro-Environmental Decision Support System* (http://www.water.ncsu.edu/watershedss): The “Educational Component” of this Web site contains fact sheets with information on a variety of techniques for management practices, including soil bioengineering and structural streambank stabilization.

Case Study: Instream Benefits for Fish and Wildlife from Careful Channelization and Channel Modification Planning

Beginning in the 1800s, Juday Creek in South Bend, Indiana was channelized and straightened to run along the edges of agricultural fields. In the mid-1980s, the channel was dredged to improve drainage, which resulted in a catastrophic decline in aquatic insect populations. In the past 20 years, runoff from urban areas has also adversely affected water quality in Juday Creek. Completed in 1999, the 18-hole Warren Golf Course on the University of Notre Dame campus would have been located on either side of Juday Creek as originally proposed and would have required nearly complete removal of streamside vegetation. This presented an opportunity to relocate and improve the stream.

A 2,200-foot reach of Juday Creek was relocated from its channelized alignment to a new location in a wooded area with an enhanced channel design. The purpose of the project was to move the stream away from a new 18-hole golf course in order to improve habitat for native trout and salmon. The channel was designed to meander with pools and runs providing a diversity of habitat. Boulders, woody debris, and gravel suitable for trout spawning were used in the design to mimic a natural stream. To control the high levels sediment transported to Juday Creek, a sediment trap, off-channel wetlands, and a filter for stormwater runoff were constructed. In addition, a system of swales and depressions were constructed to divert runoff from the golf course to wetland filtering ponds.

To build the new section of the stream, the designers used the new location for the streambed as the haul roads for all of the equipment. The stream was then excavated from one end to the other using the haul road/channel. According to Jim Lovell, a consultant on the project, "Since there was no way of getting to the haul road/channel to make adjustments once the water was released, very close attention needed to be made toward the grade of the stream." This was to allow for appropriate flows through the various habitat features. Although this technique increased construction costs overall, it enabled the riparian zone to remain intact. Construction costs were lowered, however, by decreasing up-front designs and making additional cost-saving adjustments and designs in the field. The project was completed at a cost of $194,400, a savings of 15% from the original estimated cost of $228,800.

The Juday Creek project is considered a success with the creation of new habitat for trout and salmon in this rare Midwest cold-water creek. The relocation has resulted in reduced summer high water temperatures and the discovery of 26 trout redds or spawning nests in the improved section of the stream. The new facility, officially named the William K. and Natalie O. Warren Golf Course, was designed by Coore and Crenshaw, Inc. of Austin, Texas. In 2001, the golf course became a member of the Audubon Cooperative Sanctuary Program by meeting criteria in areas such as water quality, outreach and education, and wildlife management.

Sources:
Confluence Consulting, Inc. No Date. *Juday Creek Channel Relocation and Habitat Restoration Project*. http://confluenceinc.com/projects/golf.htm. Accessed July 2003.

JFNew Consulting. No Date. *Juday Creek Relocation and Restoration*. http://www.jfnew.com/version3/body_golf.html. Accessed July 2003.

Lee, D., and J. Lovell. 1998. Urban Trout Stream Gets a Second Chance. *Land and Water* 42(1). http://www.landandwater.com/features/vol42no1/vol42no1_1.html. Accessed June 2003.

Whitten, C. 2002. Warren Golf Course and its Partner in Life, Juday Creek. *Michigan Golfer*. http://www.webgolfer.com/may02/warren.html. Accessed October 2004.

Streambank Protection

Streambank erosion is a natural process that occurs in fluvial systems. Streambank erosion can also be induced or exaggerated as a result of human activities. There are several factors within a watershed that can contribute to human induced streambank erosion. Accelerated streambank erosion related to human activity can typically be attributed to three major causes including channel modifications, reservoir construction, and land use changes (Henderson, 1986). When possible, streambank erosion problems should be addressed in the context of the entire watershed, using a systems approach that takes into consideration and accommodates natural stream processes. Approaches to addressing streambank erosion problems should involve efforts to identify and address all significant contributing factors in addition to treating the immediate symptom, bank erosion.

In general, the design of streambank protection may involve the use of several techniques and materials. Nonstructural or programmatic management practices for the prevention of streambank failures include:

- Protection of existing vegetation along streambanks
- Careful use or regulation of irrigation near streambanks, such as rerouting of overbank drainage
- Minimization of loads on top of streambanks (such as prevention of building within a defined distance from the streambed)

Additional information about these practices, as well as other streambank protection practices is available in Section 3 of this document.

Several structural practices are used to protect or rehabilitate eroded banks. These practices are usually implemented in combination to provide stability of the stream system, and they can be grouped into direct and indirect methods. Direct methods place protecting material in contact with the bank to shield it from erosion. Indirect methods function by deflecting channel flows away from the bank or by reducing the flow velocities to nonerosive levels (Henderson and Shields, 1984; Henderson, 1986). In general, indirect bank protection requires less bank grading and tree and snag removal. However, some structural methods like stone toe protection, as discussed below, can be placed with minimal disturbance to existing slope, habitat, and vegetation.

Feasibility of the practices at a site depends on the engineering design of the structure, availability of the protecting material, extent of the bank erosion, and specific site conditions such as the flow velocity, channel depth, inundation characteristics, and geotechnical characteristics of the bank. The use of vegetation alone or in combination with other structural practices, when appropriate, could further reduce the engineering and maintenance efforts.

Vegetation must be considered in light of site-specific characteristics. When vegetation is combined with low cost building materials or engineered structures, numerous techniques can be created for streambank erosion control. It is important to consider the assets and limitations when planning to use planted vegetation for streambank protection. Advantages of vegetation include the following (Allen and Leech, 1997):

- Reinforcement of soil by roots (increases bank stability)
- Exposed stalks increase resistance to flow and reduce flow velocities, causing the flow to dissipate energy against the plant (rather than the soil)
- Intercepts water
- Enhances water infiltration
- Depletes soil water by uptake and transpiration
- Acts as a buffer against the abrasive effect of transported materials
- Close-growing vegetation can induce sediment deposition
- Often less expensive than most structural methods
- Improves conditions for fisheries and wildlife
- Improves water quality
- Can protect cultural/archeological resources

Limits of vegetation include failure to grow; being subject to undermining; being uprooted by wind, water, and the freezing and thawing of ice; wildlife or livestock may feed upon it; and maintenance may be required. Chapter 3 of *Bioengineering for Streambank Erosion Control* discusses plant acquisition, handling, and timing of planting (Allen and Leech, 1997).

The following discussion provides application and effectiveness information for several types of streambank protection, including stone toe protection, live cribwalls, and vegetated gabions.

Applications and effectiveness of stone toe protection include the following (FISRWG, 1998):

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

Severe bank erosion almost always requires protecting the “toe” of the streambank. The toe lies at the bottom of slope and supports the weight of the bank. When water undermines the toe, the bank collapses. You can protect the streambank toe by using rock riprap, logs, and rock barbs combined with plants. Protect the bare soil between structures with native grasses, sedges, and rushes. Sprig plantings, grass seedings, or erosion blankets may be needed to prevent erosion until shrubs and trees establish themselves (Oregon Association of Conservation Districts 2004).

A live cribwall is used to rebuild a bank in a nearly vertical setting. It consists of a hollow, box-like interlocking arrangement of untreated log or timber members. The structure is filled with suitable backfill material and layers of live branch cuttings, which root inside the crib structure and extend into the slope. Applications and effectiveness of live cribwalls include the following (FISRWG, 1998):

- Provide protection to the streambank in areas with near vertical banks where bank sloping options are limited.
- Afford a natural appearance, immediate protection and accelerate the establishment of woody species.
- Effective on outside of bends of streams where high velocities are present.
- Appropriate at the base of a slope where a low wall might be required to stabilize the toe and reduce slope steepness.
- Appropriate above and below water level where stable streambeds exist.
- Can be complex and expensive.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.

Vegetated gabions start with wire-mesh, rectangular baskets filled with small to medium rock and soil. The baskets are then laced together to form a structural toe or sidewall. Live branches are then placed on each consecutive layer between the rock filled baskets to take root, join together the structure and bind it to the slope. Applications and effectiveness of vegetated gabions include the following (FISWRG, 1998):

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

Streambank protection structures may impact the riparian wildlife community if the stabilization effort alters the quality of the riparian habitat. For example, according to Fischenich (2003), riprap can create preferential habitat for some organisms at the expense of others, and can upset one or more entire trophic levels in the system. Riprap might also contribute to increased temperature in runoff, especially in cold water fish habitat (Roa-Espinosa, et al., n.d.b; IECA, 2003). Comparison of protected riprapped and adjacent unprotected streambanks and cultivated nearby areas along the Sacramento River showed that bird species diversity and density were significantly lower on the riprapped banks than on the unaltered sites (Hehnke and Stone, 1978). However, benthic microorganisms appear to benefit from stone revetment. Burress and others (1982) found that the density and diversity of macroinvertebrates were higher in the protected bank areas.

Fischenich (2000) notes that the steep slopes on which gabions are sometimes placed may hinder wildlife access. In addition, placement of geogrids and geotextiles can reduce the use of the site by some organisms as habitat. Some products that use a web or mesh of synthetic materials might trap small birds or mammals. Again, it is important to note that planning and evaluation are critical to optimize the benefits and reduce any impacts associated with the selection of practices to improve the physical and chemical characteristics of surface waters affected by channelization and channel modification.

For additional information, Section 3 (Streambank and Shoreline Erosion) of this document provides a more complete examination of streambank protection practices.

Levees, Setback Levees, and Floodwalls

Levees are embankments or shaped mounds constructed for flood control or hurricane protection (USACE, 1981). Many valuable techniques can be used, when applied correctly, to protect, operate, and maintain levees (Hynson et al., 1985). Evaluation of site-specific conditions and the use of best professional judgment are the best methods for selecting the proper levee protection and operation and maintenance plan. According to Hynson and others (1985), maintenance activities generally consist of vegetation management, burrowing animal control, upkeep of recreational areas, and levee repairs.

Setback levees and floodwalls are longitudinal structures used to reduce flooding and minimize sedimentation problems associated with fluvial systems. Care must be taken during construction to prevent disturbing the natural channel vegetation, cross section, or bottom slope. No immediate instream effects from sedimentation are usually caused by implementing this type of modification. The potential for long-term channel adjustments can be evaluated using methods outlined in *Channel Stability Assessment for Flood Control Projects*, EM 1110-2-1418 (USACE, 1994) at http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1418/toc.htm.

Methods to control vegetation include mowing, grazing, burning, and using chemicals. Selection of a vegetation control method should consider the existing and surrounding vegetation, desired instream and riparian habitat types and values, timing of controls to avoid critical periods, selection of livestock grazing periods, and timing of prescribed burns to be consistent with historical fire patterns. Additionally, a balance between the vegetation management practices for instream and riparian habitat and engineering considerations should be maintained to avoid structural compromise. Animal control methods are most effective when used as a part of an integrated pest management program and might include instream and riparian habitat manipulation or biological controls. Recreational area management includes upkeep of planted areas, disposal of solid waste, and repairing of facilities (Hynson et al., 1985).

The prevention of floods by dams and levees can eliminate or diminish essential ecological functions. Dams, levees and channel training structures have dramatically altered or eliminated the frequency, duration, magnitude and timing of periodic high flows. These projects significantly reduce the likelihood of floodplain inundation, block the transfer of organic matter and nutrients between river and floodplain, block plant succession, eliminate fish access to spawning areas, and rob rivers of the erosive power to restore and create a diversity of habitats (Environmental Defense 2002). Levees have had several impacts on the Snake River in Wyoming. Anthony (1998) found habitat losses, including changes in vegetation (including losses of cottonwood and riparian habitats from 1956) and changes in channel and floodplain complexity from a braided to a single channel pattern.

Siting of levees and floodwalls should be addressed prior to design and implementation of these types of projects. Proper siting of such structures can avoid several types of problems. First, construction activities should not disturb the physical integrity of adjacent riparian areas and/or wetlands. Second, by setting back the structures (offsetting them from the streambank), the relationship between the channel and adjacent riparian areas can be preserved. Proper siting and alignment of proposed structures can be established based on hydraulic calculations, historical flood data, and geotechnical analysis of riverbank stability.

Grade Control Structures

There are two basic types of grade control structures. The first type can be referred to as a bed control structure because it is designed to provide a hard point in the streambed that is capable of resisting the erosive forces of the degradational zone. The second type can be referred to as a hydraulic control structure because it is designed to function by reducing the energy slope along the degradational zone to the point where the stream is no longer capable of scouring the bed. The distinction between the operating processes of these two types is important whenever grade control structures are considered (Biedenharn and Hubbard, 2001).

Design considerations for siting of grade control structures include determining the type, location, and spacing of structures along the stream, along with the elevation and dimensions of structures. Siting grade control structures can be considered a simple optimization of hydraulics and economics. However, these factors alone are usually not sufficient to define optimum siting conditions. Hydraulic considerations must be integrated with a host of other factors that can vary from site to site to determine the final structure plan. Some of the more important factors to be considered when siting grade control structures are discussed more specifically in the U.S. Army Corps of Engineers' *Design Consideration for Siting Grade Control Structures* (Biedenharn and Hubbard, 2001).

When carefully applied, grade control structures can be highly versatile in establishing human and environmental benefits in stabilized channels. To be successful, application of grade control structures should be guided by analysis of the stream system both upstream and downstream from the area to be reclaimed (CASQA, 2003).

In some cases, grade control structures can be designed to allow fish passage. However, some grade control structures typically obstruct fish passage. In many instances, fish passage is a primary consideration and may lead engineers to select several small fish passable structures in lieu of one or more high drops that would restrict fish passage. In some cases, particularly when drop heights are small, fish are able to migrate upstream past a structure during high flows. In situations where structures are impassable, and where the migration of fish is an important concern, openings, fish ladders, or other passageways must be incorporated into the structure's design (Biedenharn and Hubbard, 2001). Refer to Section 2 for information about fish passage practices.

Check dams, which are a type of grade control structure, are small dams constructed across an influent, intermittent stream, or drainageway to reduce channel erosion by restricting flow velocity. They can serve as emergency or temporary measures in small eroding channels that will be filled or permanently stabilized at a later date, such as in a construction setting. Check dams can also be installed in eroding gullies to serve as permanent measures that fill up with sediment over time. In permanent usage, when the impounded area is filled, a relatively level surface or delta is formed over which the water flows at a noneroding gradient. The water then cascades over the dam through a spillway onto a hardened apron. A series of check dams may be constructed along a stream channel of comparatively steep slope or gradient to create a channel consisting of a succession of gentle slopes with cascades in between.

Check dams can be nonporous (constructed from concrete, sheet steel, or wet masonry) or they can be porous (using available materials such as straw bales, rock, brush, wire netting, boards, and posts). Porous dams release part of the flow through the structure, decreasing the head of flow over the spillway and the dynamic and hydrostatic forces against the dam. Nonporous dams are durable, permanent, and more expensive, while porous dams are simpler, more economical to construct, and temporary. Maintenance of check dams is important, especially the areas to the sides of the dam. Regular inspections, particularly after high flow events, should be performed to observe and repair erosion at the sides of the check dams. Excessive erosion could dislodge the check dam, create additional channel erosion, and add more sediment to the streambed.

Vegetative Controls

Streambank protection using vegetation is a commonly used practice, particularly in areas of low water veolocities. Vegetative cover, also used in combination with structural practices, is often relatively easy to establish and maintain, and is visually attractive (USACE, 1983).

Emergent vegetation provides two levels of protection. First, the root system helps to hold the soil together and increases overall bank stability by forming a binding network. Second, the exposed stalks, stems, branches, and foliage provide resistance to the streamflow, causing the flow to lose part of its energy by deforming the plants rather than by removing the soil particles. Above the waterline, vegetation protects against rainfall impact on the banks and reduces the velocity of the overland flow during storm events.

Vegetative controls are not suitable for all sites, especially those sites with severe erosion due to high flow rates or channel velocities. Refer to WSDOT's *Hydraulics Manual*, Chapter 4, (http://www.wsdot.wa.gov/eesc/design/hydraulics/Manual/Rev3Publications/Chapter%204.pdf) for information on calculating flow rates or channel velocities. Stabilization measures should only be implemented after a careful evaluation of the stream and the surrounding area. A knowledgeable fluvial geomorphologist may be helpful with this evaluation. In addition, plant species should be selected with care; native plant species should be used whenever possible. Appropriate species can be determined by consulting horticulturalists and botanists for plant selection assistance. The USDA-FS guide, *A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization* (http://www.fs.fed.us/publications/soil-bio-guide/) provides a list of plants for soil bioengineering associated systems. The International Erosion Control Association (IECA) publishes a products and services directory listing sources of plant material and professional assistance. Information about IECA is available at http://ieca.org/.

In addition to its bank stabilization potential, vegetation can provide pollutant-filtering capacity. Pollutant and sediment transported by overland flow may be partly removed as a result of a combination of processes including reduction in flow pattern and transport capacity, settling and deposition of particulates, and eventually nutrient uptake by plants. For more information about vegetative controls, see Section 3 of this document.

Case Study: Vegetative Control of an Illinois Watershed

Court Creek Watershed in Knox County, Illinois is located within a glaciated region where highly erodible soils line the stream and riverbanks. With a drainage area of 98 square miles, Court Creek watershed is plagued by a variety of problems, including flooding and streambank erosion due to the rolling topography and highly erodible soils within the watershed. To combat sediment loss, vegetative stabilization measures were designed in 1986. Willow posts, willow cuttings, and tree revetments were used to reduce the amount of erosion to the Court Creek Watershed. Dormant, 12 feet long willow posts were planted at moderately eroding sites during the spring and at several sites in the winter. The willow posts were planted 6 feet deep and in 4 feet by 4 feet diamond patterns along the streambank. Since the willow posts were in their dormant stage, the survival rates were high without regard to the time of year planted. The willow posts survived both ice flows and flooding during the year. Tree revetments and willow cuttings were installed at moderately eroding sites. To encourage sediment deposits, native riparian vegetation was planted behind the willow cuttings and trees revetments. This measure assisted in slope stabilization until the willow cuttings could establish their root base.

Four watersheds, including the Court Creek watershed, were selected to participate in the Illinois Pilot Watershed Program. The program is designed to address watershed issues such as erosion, flooding, and deposition of nutrients/sediment in streams and to examine the effects of management practices on improving the entire watershed. These pilot watersheds receive planning assistance, including monetary planning grants, technical support from the partner agencies, and extensive assessment of practices implemented. The Illinois State Water Survey installed continuous stream gauging stations and monitoring and analyzed hydrology, sediment, and nutrients in the pilot and reference watershed. Fish, macroinvertebrate (benthos) and stream habitat have been sampled in Court Creek and its reference watersheds. Monitoring began in 1998 and will continue for the duration of the Pilot Watershed Program, which is projected to be a minimum of 10 years.

Sources:
Heyer, T., and Bitz, J. 1998. Vegetative Measures for Streambank Stabilization: Case Studies in Illinois and Missouri. http://www.na.fs.fed.us/spfo/pubs/n_resource/stream/str_cov.htm. Accessed April 2004.

Hogan, A.M. 2003. Agency Collaboration Launches Illinois Pilot Watershed Program. *Agro-Ecology News and Perspectives* 8(1). http://www.aces.uiuc.edu/~asap/news/v8n1/pilot_watershed.html. Accessed July 2003.

Illinois Natural History Survey Reports. 2000. *Illinois Pilot Watershed Program.* http://www.inhs.uiuc.edu/inhsreports/sum-2000/watershed.html. Accessed July 2003.

Instream Sediment Load Controls

Streambanks can be protected or restored either by increasing resistance of the bank to erosion or by decreasing the energy of the water at the point of contact with the bank, for example by deflecting or interrupting flows (Henderson, 1986). Instream sediment can be controlled by using several structural, vegetative, or bioengineered practices, depending on the management objective and the source of sediment. Streambank protection and channel stabilization practices, including various types of revetments, grade control structures, and flow restrictors, have been effective in controlling sediment production caused by streambank erosion. Designs should match the protection capability of the treatment to the erosion potential of each stream zone. For example, riprap may be needed at the toe of a slope to protect it from undercutting combined with tree revetments to deflect flows and provide protection for live stakings that will develop permanent support. The growing body of research indicates management techniques that emulate nature and work with natural stream processes are more successful and economical.

Significant amounts of instream sediment deposition can be prevented by controlling bank erosion processes and streambed degradation. Channel stabilization structures can also be designed to trap sediment and decrease the sediment delivery to desired areas by altering the transport capacity of the stream and creating sediment storage areas. In regulated streams, alteration of the natural streamflow, particularly the damping of peak flows caused by surface water regulation and diversion projects, can increase streambed sediment deposits by impairing the stream's transport capacity and its natural flushing power. Sediment deposits and reduced flow alter the channel morphology and stability, the flow area, the channel alignment and sinuosity, and the riffle and pool sequence. Such alterations have direct impacts on the aquatic habitat and the fish populations in the altered streams (Reiser et al., 1985).

Use of hydraulic structures to stabilize stream channels, as well as to control stream sediment load and transport, is a common practice. In general, these structures function to:

- Retard further downward cutting of the channel bed
- Retard or reduce the sediment delivery rate
- Raise and widen the channel beds
- Reduce the stream grade and flow velocities
- Reduce movement of large boulder
- Control the direction of flow and the position of the stream

Noneroding Roadways

Disturbances along the streambank that result from activities associated with the operation and maintenance of channelization projects can lead to additional nonpoint source pollution impacts to the stream. An example of human-induced activities can be found with erosion associated with roadways. Rural road construction, streamside vehicle operation, and stream crossings usually result in significant soil disturbance and create a high potential for increased erosion processes and sediment transport to adjacent streams and surface waters. Erosion during and after construction of roadways can contribute large amounts of sediment and silt to runoff waters, which can deteriorate water quality and lead to fish kills and other ecological problems (USEPA, 1995b).

Road construction involves activities such as:

- Clearing of existing native vegetation along the road right-of-way
- Excavating and filling the roadbed to the desired grade
- Installation of culverts and other drainage systems
- Installation, compaction, and surfacing of the roadbed

Although most erosion from roadways occurs during the first few years after construction, significant impacts may result from maintenance operations using heavy equipment, especially when the road is located adjacent to a waterbody. In addition, improper construction and lack of maintenance may increase erosion processes and the risk for road failure. To minimize erosion and prevent sedimentation impacts on nearby waterbodies during construction and operation periods, streamside roadway management needs to combine proper design for site-specific conditions with appropriate maintenance practices.

Road Construction and Fish Habitat

The potential for road construction to increase sediment delivery to streams has important implications for certain species of fish. Salmonids and other fish that nest on stream bottoms are very susceptible to sediment pollution due to the settling of sediment that can smother nests and deplete the oxygen available to the eggs. The eggs, buried 1 to 3 feet deep in the gravel redd, rely on a steady flow of clean, cold water to bring oxygen and remove waste products. The redd is a depression in the gravel streambed where the eggs are laid, and the depression creates a Venturi effect, drawing water down into the gravel. If the water in the stream above is full of fine sediment, then sediment is drawn down into the redd and smothers the eggs. Additional information about road construction and fish habitat is available in Chapter 3 of EPA's *National Management Measures to Control Nonpoint Source Pollution from Forestry* (USEPA, 2005e).

Stream Crossings and Fish Passage

Common conditions at stream crossing culverts that can create barriers to fish passage include excess drop at the culvert outlet, high velocity within the culvert barrel, inadequate depth within the culvert barrel, turbulence within the culvert, and debris accumulation at the culvert inlet. Barriers to fish passage can be complete, partial, or temporal. Complete barriers block the use of the upper watershed, often the most productive spawning habitat in the watershed for migratory species of fish. Partial barriers block smaller or weaker fish of a population. Culverts are therefore designed to accommodate smaller or weaker individuals of target species, including juvenile fish. Temporal barriers block migration during some part of the year. They can delay some fish from arriving at upstream locations, which for some fish (anadromous salmonids that survive a limited amount of time in fresh water) can cause limited distribution or mortality (USEPA, 2005e).

Barriers at culverts can result from improper initial design or installation, or they can occur because of channel degradation that leaves culvert bottoms elevated above the downstream channel. Changes in hydrology from an extensive road network can be a primary reason for channel degradation, and older culverts that might have been adequate when installed can become inadequate for fish passage when channel degradation or land use changes cause changes in stream channel hydrology. When such changes occur in a watershed, inspect culverts and, if necessary, replace them with ones that meet specifications. Additional information about design and applicability of culverts and how they can affect fish passage is available from EPA's *National Management Measures to Control Nonpoint Source Pollution from Forestry* (USEPA, 2005e).

General Road Construction Considerations

Road design and construction activities that are tailored to the topography and soils and that take into consideration the overall drainage pattern in the watershed where the road is being constructed can prevent road-related water quality problems. Lack of adequate consideration of watershed and site characteristics, road system design, and construction techniques appropriate to site circumstances can result in mass soil movements, extensive surface erosion, and severe sedimentation in nearby waterbodies. The effect that a road network has on stream networks largely depends on the extent to which the networks are interconnected. Road networks can be hydrologically connected to stream networks where road surface runoff is delivered directly to stream channels (at stream crossings or via ditches or gullies that direct flow off the road and to a stream) and where road cuts transform subsurface flow into surface flow (in road ditches or on road surfaces that deliver sediment and water to streams much more quickly than without a road present). The combined effects of these drainage network connections are increased sedimentation and peak flows that are higher and arrive more quickly after storms. This in turn can lead to increased instream erosion and stream channel changes. This effect is strongest in small watersheds (USEPA, 2005e).

Site characteristics should be considered during construction planning. On-site verification of information from topographic maps, soil maps, and aerial photos can ensure that locations where roads are to be cut into slopes or built on steep slopes or where skid trails, landings, and equipment maintenance areas are to be located are appropriate to the use. If an on-site visit indicates that changes to the road construction can reduce the risk of erosion, the project manager can make these changes prior to construction, and in some cases as the project progresses (USEPA, 2005e).

Road drainage features tailored to the site and its conditions prevent water from pooling or collecting on road surfaces and thereby prevent saturation of the road surface, which can lead to rutting, road slumping, and channel washout. Many of the roads associated with channelization projects are temporary or seasonal-use roads, and their construction should not generally involve the high level of disturbance generated by the construction of permanent, high-standard roads. However, temporary or low-standard roads still need to be constructed and maintained to prevent erosion and sedimentation (USEPA, 2005e).

Erosion control practices need to be applied while a road is being constructed, when soils are most susceptible to erosion, to minimize soil loss to waterbodies. Since sedimentation from roads often does not occur incrementally and continuously, but in pulses during large rainstorms, it is important that road, drainage structure, and stream crossing design take into consideration a sufficiently large design storm that has a good chance of occurring during the life of the project. Such a storm might be the 10-year, 25-year, 50-year, or even 100-year, 12- to 24-hour return period storm. Sedimentation cannot be completely prevented during or after road construction, but the process is exacerbated if the road construction and design are inappropriate for the site conditions or if the road drainage or stream crossing structures are insufficient (USEPA, 2005e).

When constructing a new road, it is useful to consider the surface shape and composition of the road, slope stabilization; how road construction will affect fish habitat, how stream crossing will affect fish passage, and considerations to make when considering building a road through a wetland (USEPA, 2005e). It is important to remember that CWA section 404 requires that wetlands or other waters of the U.S. be avoided if at all practical, and that unavoidable impacts be minimized. Refer to the discussion of CWA section 404 in the introduction for additional information.

Road Surface Shape and Composition

The shape of a road is an important component of runoff control. Road drainage and runoff control are obtained by shaping the road surface to be insloping, outsloping, or crowned. Insloping roads can be effective where soils are highly erodible and directing runoff directly to the fill slope would be detrimental. Outsloped roads tend to dissipate runoff more than insloped roads, which concentrate runoff at cross drain locations, and are useful where erosion of the backfill or ditch soil might be a problem. Crowned roads are particularly suited to two lane roads and to steep single-lane roads that have frequent cross drains or ditches and ditch relief culverts (USEPA, 2005e). These road surface shapes are illustrated in Figure 1.5.

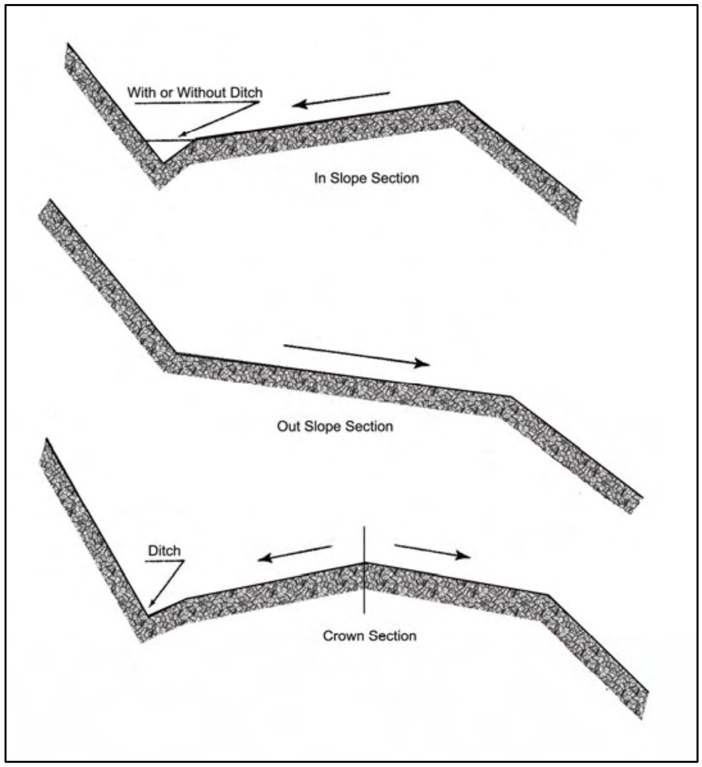


Figure 1.5 Types of Road Surface Shapes (Source: USEPA, 2005e)

Road surfaces need to have and maintain one of these shapes at all points to ensure good drainage. Crowns, inslopes, and outslopes will quickly lose effectiveness if not maintained frequently, due to micro-ruts created by traffic when the road surface is damp or wet (USEPA, 2005e).

The composition of a road surface is another factor that can be controlled to effectively control erosion from the road surface and slopes. It is important to choose a road surface that is suitable to the topography, soils, and intended use. Road surfaces can be formed from native material, aggregates, asphalt, or other suitable materials, and any of these surface compositions can be shaped in one of the ways discussed above. Surface protection of the roadbed and cut-and-fill slopes with a suitable material can (USEPA, 2005e):

- Minimize soil losses during storms
- Reduce frost heave erosion production
- Restrain downslope movement of soil slumps
- Minimize erosion from softened roadbeds

Slope Stabilization

Road cuts and fills can be a large source of sediment when a rural road is constructed. Stabilizing back slopes and fill slopes as they are constructed is an important process in minimizing erosion from these areas. Combined with graveling or otherwise surfacing the road, establishing grass or using another form of slope stabilization can significantly reduce soil loss from road construction. If constructing on an unstable slope is necessary, consider consulting with an engineering geologist or geotechnical engineer for recommended construction methods and to develop plans for the specific road segment. Unstable slopes that threaten water quality should always be considered unsuitable for road building.

Planting grass on cut-and-fill slopes of new roads can effectively reduce erosion, and placing forest floor litter or brush barriers on downslopes in combination with establishing grass is also an effective means to reduce downslope sediment transport. Grass-covered fill is generally more effective than mulched fill in reducing soil erosion from newly constructed roads because of the roots that hold the soil in place, which are lacking with any other covering placed on the soil. Because grass needs some time to establish itself, a combination of straw mulch with netting to hold it in place can be used to cover a seeded area and effectively reduce erosion during the period while grass is growing. The mulch and netting provide immediate erosion control and promote grass growth (USEPA, 2005e).

Wetland Road Considerations

Sedimentation is a concern when considering road construction through wetlands. Because of the fragility of these ecosystems, where an alternative route exists, it is better to avoid putting a road through a wetland. If it is necessary to traverse a wetland, implement BMPs suggested by the state. Road construction or maintenance for certain farming, forestry, or mining activities might be exempt under CWA section 404. However, to qualify for the exemption, the roads must be constructed and maintained following application of specific BMPs designed to protect the aquatic environment (USEPA, 2005e).

Design and Construction Practices

The following practices related to roadways are suggested in EPA’s *National Management Measures to Control Nonpoint Source Pollution from Forestry* (USEPA, 2005e).

Best management practices to consider for siting of roadways include (USEPA, 1993):

- Systematically design transportation systems to minimize total mileage.
- Design roads to follow the natural topography and contour, minimizing alteration of natural features.
- Minimize the number of stream crossings.
- Design culverts and bridges for minimal impact on water quality and remove temporary stream crossings upon completion of operations.
- Avoid construction of new roads in a streamside management area.
- Inspect roads to determine the need for structural maintenance.
- Conduct maintenance activities so that chemical contaminants or pollutants are not introduced into surface waters.

Road surface construction practices to consider include the following:

- Follow the design developed during construction planning to minimize erosion by properly timing and limiting ground disturbance operations.
- Consider geotextiles on road sections requiring aggregate material layers for surfacing.

- Protect access points to the site that lead from a paved public right-of-way with stone, wood chips, corduroy logs, wooden mats, or other material to prevent soil or mud from being tracked onto the pavement.
- Use pioneer roads to reduce the amount of area disturbed and ensure the area's stability.
- During road construction, operate equipment to minimize unintentional movement of excavated material downslope.
- Prevent slash from entering streams; promptly remove any that accidentally enters streams to prevent problems related to slash accumulation.
- When soil moisture is high, promptly suspend earthwork operations and weather proof the partially complete work.
- Properly dispose of organic debris generated during road construction.
- Compact the road base at the proper moisture content, surfacing, and grading to give the designed road surface drainage shaping.

Road surface drainage practices to consider include the following:

- Install surface drainage controls at intervals that remove storm water from the roadbed before the flow gains enough volume and velocity to erode the surface. Avoid discharge onto fill slopes unless the fill slope has been adequately protected.
- Install turnouts, wing ditches, and dips to disperse runoff and reduce the amount of road surface drainage that flows directly into watercourses.
- Install appropriate sediment control structures (e.g., sediment traps, brush barriers, silt fences, filter strips) to trap sediment transported by runoff and prevent its discharge into the aquatic environment.

Road slope stabilization practices to consider include the following:

- Visit locations where roads are to be constructed on steep slopes or cut into hillside to verify that these are the most favorable locations for the roads.
- Use straw bales, straw mulch, grass seeding, hydromulch, and other erosion control and revegetation techniques to stabilize slopes and minimize erosion. Straw bales and straw mulch are temporary measures used to protect freshly disturbed soils and are effective when implemented and maintained until adequate vegetation has established to prevent erosion.
- Compact the fill to minimize erosion and ensure road stability.
- Revegetate or stabilize disturbed areas, especially at stream crossings.

Stream crossing practices to consider include the following:

- Based on information obtained from site visits, make any alterations to the harvesting plan that are necessary or prudent to protect surface waters from sedimentation or other forms of pollution and to ensure the adequacy of fish passage.
- Construct stream crossings to minimize erosion and sedimentation.
- Install a stream crossing that is appropriate to the situation and conditions.
- Construct bridges and install culverts during periods when streamflow is low.

- Do not perform excavation for a bridge or a large culvert in flowing water. Divert water around the work site during construction with a cofferdam or stream diversion.
- Protect embankments with mulch, riprap, masonry headwalls, or other retaining structures.
- Construct ice bridges in streams with low flow rates, thick ice, or dry channels during winter. Ice bridges might not be appropriate on large waterbodies or areas prone to high spring flows.

Fish passage practices to consider include:

- Avoid construction during egg incubation periods on streams with spawning areas.
- Design and construct stream crossings for fish passage according to site-specific information on stream characteristics and the fish populations in the stream where the passage is to be installed.

Operation and Maintenance

Inspection and maintenance of erosion and sediment control BMPs after construction is completed is important to ensure that BMPs are operating properly and effectively. Some key operation and maintenance procedures include (USEPA, 1995b):

- *Prepare and adhere to a schedule of regular maintenance for temporary erosion and runoff control BMPs.* Two critical maintenance operations are cleaning out accumulated sediment and replacing worn-out or deteriorated materials, such as silt fence fabrics, so that the effectiveness of the controls is maintained. Maintenance can include dredging and reshaping sediment basins and revegetating the slopes of grassed swales.
- *Remove temporary BMPs from construction areas when they are no longer needed and replace them, where appropriate, with permanent BMPs.*
- *Schedule and periodically inspect and maintain permanent erosion and runoff controls.* This should include a periodic visual inspection of permanent BMPs during runoff conditions to ensure that the controls are operating properly. Clean, repair, and replace permanent erosion and runoff control BMPs when necessary.

General Maintenance BMPs

General maintenance BMPs include the following (USEPA, 1995b):

- *Seeding with grass and fertilizing* to promote strong growth provide long-term stabilization of exposed surfaces. Disturbed areas can be seeded and fertilized during construction and after it is completed. Sufficient watering and refertilizing 30 to 40 days after the seeds germinate help establish dense growth.
- *Seeding with grass and overlaying with mulch or mats* is done to stabilize cleared or freshly seeded areas. Types of mulches include organic materials, straw, wood chips, bark or other wood fibers, or decomposed granite and gravel. Mats are made of natural or synthetic material and are used to temporarily or permanently stabilize soil.
- *Wildflower cover* has been successfully used to provide attractive vegetation along roadways and erosion control. Careful consideration must be given to visibility, access, soil condition, climate, and maintenance when choosing sites for wildflower cover.

- *Sodding* with established grass blankets on prepared soil provides a quick vegetative cover to lessen erosion. Proper watering and fertilizing are important to ensure the vitality of newly placed sod.

Permanent Control BMPs

Several permanent control BMPs (including structural and nonstructural ESC devices) that may be used to prevent erosion from roadways include the following (USEPA, 1995b):

- *Grassed swales* are shallow, channeled grassed depressions through which runoff is conveyed. The grass slows the flow of runoff water, allowing sediment to settle out and water to infiltrate into the soil. Grassed swales can remove small amounts of pollutants such as nutrients and heavy metals. Check dams (see below) can be added to grassed swales to further reduce flow velocity and promote infiltration and pollutant removal.
- *Filter strips* are wide strips of vegetation located to intercept overland sheet flows of runoff. They can remove organic material, sediment, and heavy metals from runoff, but cannot effectively treat high-velocity flows. Filter strips can consist of any type of dense vegetation from woods to grass. They are best suited to low-density developments.
- *Terracing* breaks a long slope into many flat surfaces where vegetation can become established. Small furrows are often placed at the edge of each terraced step to prevent runoff from eroding the edge. Terracing reduces runoff velocity and increases infiltration.
- *Check dams* are small temporary dams made of rock, logs, brush, limbs, or another durable material, placed across a swale or drainage ditch. By reducing the velocity of storm flows, sediment in runoff can settle out and erosion in the swale or ditch is reduced.
- *Detention ponds or basins* temporarily store runoff from a site and release it at a controlled rate to minimize downstream flooding. Pollutant removal effectiveness is quite good for well-designed basins. Effectiveness is greatest for suspended sediments (80 percent or more removal) and related pollutants such as heavy metals.
- *Infiltration trenches* are shallow, three to eight feet deep (.91 to 2.44 m), excavated trenches that are backfilled with stone to create underground reservoirs. Runoff is diverted into the trenches, from which it percolates into the subsoil. Properly designed infiltration trenches effectively remove sediment from runoff and can remove some other runoff pollutants.
- *Infiltration basins* are relatively large, open depressions produced by either natural site topography or excavation. When runoff enters an infiltration basin, the water percolates through the bottom or the sides and the sediment is trapped in the basin. The soil where an infiltration basin is built must be permeable enough to provide adequate infiltration. Some pollutants other than sediment are also removed in infiltration basins.
- *Constructed wetlands* are artificial wetlands that emulate the functions of natural wetlands, including filtering sediment, nutrients, and some heavy metals from runoff waters. Wetlands, including constructed wetlands, are areas inundated by waters for sufficient time to support vegetation adapted for life in saturated soil conditions.

The following sources may be used to obtain additional information on noneroding roadways:

- *Controlling Nonpoint Source Runoff Pollution from Roads, Highways, and Bridges* (http://www.epa.gov/owow/nps/roads.html)
- The "Road Maintenance Video Set" is a five-part video series developed for USDA Forest Service equipment operators that focuses on environmentally sensitive ways of maintaining low volume roads. (http://www.epa.gov/owow/nps/maint_videoset.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)
- *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)
- *Erosion, Sediment, and Runoff Control for Roads and Highways* (http://www.epa.gov/owow/nps/education/runoff.html)
- *Recommended Practices Manual: A Guideline for Maintenance and Service of Unpaved Roads* (http://www.epa.gov/owow/nps/unpavedroads.html)
- *Low-Volume Roads Engineering Best Management Practices Field Guide* (http://zietlow.com/manual/gk1/web.doc)
- *Massachusetts Unpaved Roads BMP Manual* (http://www.mass.gov/dep/brp/wm/files/dirtroad.pdf)

D. Costs

Remember that costs will vary greatly, based on factors such as location, project type, materials used, project scale, and local or state regulatory requirements.

Cost is an important factor to consider when planning for streambank stabilization and restoration projects. It is often included as criteria for design and may influence selection of a treatment or dictate what protection techniques may be considered as alternatives. Bank-protection costs include design, materials, construction and dewatering, revegetation, monitoring, maintenance, mitigation and permitting. Design costs are typically 10 to 20 percent of construction costs, including revegetation. Monitoring, maintenance and permitting costs vary widely among project types and specific regulatory requirements (WDFW et al., 2003)

Bank protection costs are highly variable and can range from a few dollars to hundreds of dollars per foot of bank protected, depending upon the project site, design criteria and scale of the project. Cost is also highly dependent on the site. Site-dependent variables include materials availability and hauling cost, dewatering methods, site and construction access, utilities, mitigation requirements and irrigation (WDFW et al., 2003).

In addition to the direct costs of bank protection, costs associated with the following items should be considered in order to estimate the full cost of a bank-protection action (these are discussed in more detail in the *Risk Assessment* section of Chapter 4, *Considerations for a Solution*, WDFW et al., 2003):

- Repair of damage to property and infrastructure
- Relocation of at-risk facilities
- Compliance with habitat-protection requirements under the federal Endangered Species Act or other laws
- Channel restoration to prevent further habitat losses caused by the protection action
- Habitat mitigation for the duration of the project's impact, including monitoring and adjustments.

Mitigation requirements often include specific limitations on project timing, access, type of equipment allowed and damage to the natural streambank, all of which will affect project cost.

Table 1.2 describes typical costs of materials used in projects to protect streambanks.

Table 1.2 Typical Costs of Materials Used in Streambank Protection Projects

Material Type	Unit of Measure	Unit Cost
Rock Materials		
Riprap	Cubic yard	$60 – $80
Pit run	Cubic yard	$30 – $40
River gravel	Cubic yard	$40 – $80
River cobble	Cubic yard	$80 – $100
Boulders (2 – 4 feet diameter)	Cubic yard	$40 – $60
Filter gravel	Cubic yard	$40 – $60 (placed)
Soil Materials		
Topsoil (standard grade)	Cubic yard	$10 – $15
Structural fill	Cubic yard	$60 – $80, includes compaction
Fabric Materials		
Woven coir fabric	Square yard	$2.00 – $3.00
Nonwoven coir	Square yard	$1.00 – $2.00
Nonwoven geosynthetic filter fabric	Square yard	$0.50 – $0.68
Biodegradable geotextile fabric	Square yard	$2.85 – $3.00
Artificial Materials		
Doloes	Each	$200 – $900
Plant Materials		
Soil preparation	Square yard	$2.25 (includes tilling, grading, and hand raking)
Live cuttings	Each	$2 – $5 (planted)
Tubelings	Each	$1 – $4 (planted)
Conservation plugs	Each	$1 – $4 (planted)
Grass seed	Acre	$750
Evergreen trees (3 feet height)	Each	$15
Deciduous trees (3/4 inch caliper)	Each	$20

Material Type	Unit of Measure	Unit Cost
Shrubs (1 – 2 gallon)	Each	$8 – $12
Ground cover (1 gallon)	Each	$8 – $10
Mulch	Square yard	$2 – $5
Hydroseeding	Square yard	$0.04
Wood Materials		
Large wood with rootwad	Each	$500 – $750
Large wood without rootwad	Each	$200 – $300
Miscellaneous		
Wooden stakes	Each	$0.40 – $0.75
Cable	Linear foot	$0.75 (1/2 inch diameter)
Cable clamps	Each	$0.54 (cost varies based on cable diameter)

* Note: These are installed costs, which include purchase of the material, hauling to the site, excavation, spoilage, and installation. Plant material costs depend on the maturity of the plants purchased. Seed and tubeling stock are sold at a fraction of the cost of more mature stock, although substantially more maintenance is required to guarantee survival. Costs are based on 2003 values.

Source: WDFW et al., 2003

Table 1.3 describes construction and dewatering costs associated with projects.

Table 1.3 Range of Costs for Construction and Dewatering Components of Bank Protection Projects in Washington State

Construction/Dewatering Components	Unit of Measure	Unit Cost
Access and Haul Raods		
Access with geotextile base	Linear foot	$10 – $20
Dewatering		
Portadam coffer dam (dry)	Linear foot	$25 – $40
Cement barrier (wet)	Linear foot	$10 – $25
Gravel barrier	Linear foot	$5 – $25
Sediment Control		
Silt Fence	Linear foot	$1.50 – $2.50
Straw/hay bale barrier	Linear foot	$1.00 – $3.00

Note: Construction costs include mobilization, installation (and eventual removal) of access and haul roads, dewatering, sediment control, and bank treatment construction. Costs are based on 2003 values.

Source: WDFW et al., 2003

Table 1.4 describes cost ranges for streambank protection techniques.

Table 1.4 Estimated Cost Ranges for Various Streambank-Protection Techniques

Material	Unit of Measure	Unit Cost
Instream Flow-Redirection Techniques		
Groin (rock)	Each	$2,000 – $5,000
Groin (doloes)	Each	$12,000 – $45,000
Buried groin (rock)	Each	$2,000 – $5,000
Barb (rock)	Each	$2,000 – $5,000
Engineered log jam	Each	$1,800 – $80,000
Drop structures	Each	$100 – $40,000
Porous weir	Each	$100
Structural Bank Protection Techniques		
Anchor points	n/a	n/a
Roughness trees	Linear foot	$40 – $80
Riprap	Linear foot	$30 – $90
Log tow	Linear foot	$20 – $60
Rock tow	Linear foot	$20 – $40
Log cribwalls	Linear foot	$250 – $350
Artificial streambank protection materials and systems	n/a	n/a
Biotechnical Bank Protection Techniques		
Woody plantings (at 3 feet spacing)	Acre	$25,000 – $30,000
Herbaceus cover	Acre	$7 – $15
Soil reinforcement	Linear foot	$50 – $400
Coir logs	Linear foot	$8 – $30
Bank reshaping	Linear foot	$10 – $45
Fascines	Linear foot	$8 – $120
Brush layers and mattresses	Linear foot	$37 – $50
Internal Bank Drainage Techniques		
Subsurface drainage systems	n/a	n/a

Note: Costs are for materials and construction only and do not include design or post-construction components of a project. Cost ranges in many cases vary considerably. The costs listed in this table should be considered rough estimates and used only on a conceptual basis for comparison. Costs are based on various bank treatments installed primarily in Washington State between 1995 and 2000.

Source: WDFW et al., 2003

Costs in the tables above are estimates. When planning a project, be sure to research costs to determine a more accurate cost estimate for the project.

Case Study: Silver Spring Brook Watershed Demonstration Project -Landowners' Cooperation Plus Town's Commitment Equals Success

The Silver Spring Brook watershed in Limestone, Maine encompasses about 1,400 acres, 42 percent of which are cropland. The remaining acreage is either forested or in the Conservation Reserve Program. Silver Spring Brook benefited the town of Limestone as the drinking water supply, a cold-water habitat for native brook trout (*Salvelinus fontinalis*), and the feeder for the community swimming area. Over the years, sedimentation from the field roads, ditches, stream crossings, and sections of some fields were significant contributors to the stream's degradation. In 1989 the Maine Department of Environmental Protection submitted an Assessment Report to EPA of the State's major non-point source (NPS) problems. Silver Spring was identified as a waterbody in need of funding due to heavy sedimentation, which resulted in high raw turbidity readings, exceeding federal drinking water standards, threatening the cold-water habitat for native brook trout, and endangering the town's only recreational swimming area.

Following EPA's approval, the state was eligible to receive Section 319 funds to implement the State's NPS Plan to address pollution sources. Beginning in 1997, the Town of Limestone formed a partnership with the Central Aroostook Soil and Water Conservation District to plan and implement a Section 319 project. The project was funded through the Maine Department of Environmental Protection (MDEP) and received input from the U.S. Department of Agriculture and the Natural Resources Conservation Service. There were two key components to the project's success. One was the cooperation of adjacent landowners—all farmers—and the other was the town's commitment of municipal staff and equipment for the installation of the farm road best management practices (BMPs).

Between 1997 and 1999, a variety of erosion controls and land use practices were installed throughout the project area. Diversion ditches were constructed to divert the flow of water away from the brook, and turnouts were built to divert road flow into the woods. Culverts were replaced and new ones added, surrounded by riprap, to allow unimpeded stream flow. A sediment pond was also constructed to collect runoff from cropland.

The farm access road that crossed the stream was graded and crowned, and the stream crossing was repaired and stabilized. Workers installed drain tile to control the water from a natural spring that had been causing erosion and deterioration of the farm access road. They reshaped and stabilized existing road ditches and constructed new ditches. Grass buffers were also established along the fields. With only partial installation of the BMPs completed, there was a 38% decrease in turbidity in 1997-1998, allowing the water quality to meet federal drinking water standards. A measurable decrease in turbidity has significantly benefited the native brook trout habitat. Lower turbidity readings have also resulted in improved swimming conditions and recreational opportunities for the community.

Sources:

Maine Department of Environmental Protection. *Silver Spring Brook Watershed Demonstration Project.* http://www.state.me.us/dep/blwq/docwatershed/silver.pdf. Accessed July 2003.

Maine Department of Environmental Protection. 1999. *Maine Nonpoint Source Control Program: Program Upgrade and 15 Year Strategy*. http://www.state.me.us/dep/blwq/docwatershed/npsstrategy.pdf. Accessed July 2003.

USEPA. 2002. *Silver Spring Brook Watershed Demonstration Project: Landowners' Cooperation Plus Town's Commitment Equals Success.* U.S. Environmental Protection Agency, Section 319 Success Stories Vol. III. http://www.epa.gov/owow/nps/Section319III/ME.htm. Accessed June 2003.

Management Measure for Instream and Riparian Habitat Restoration

Management Measure
1) Evaluate the potential effects of proposed channelization and channel modification on instream and riparian habitat. 2) Plan and design channelization and channel modification to reduce undesirable impacts. 3) Develop an operation and maintenance program for existing modified channels that includes identification and implementation of opportunities to restore instream and riparian habitat in those channels.

A. Introduction

Implementation of this management measure is intended to occur concurrently with the implementation of the Management Measure for Physical and Chemical Characteristics of Channelized or Modified Surface Waters (see previous management measure discussion). This management measure pertains to surface waters where channelization and channel modification have altered or have the potential to alter instream and riparian habitat, such that historically present fish or wildlife are adversely affected. This management measure is intended to apply to any proposed channelization or channel modification project to determine changes in instream and riparian habitat and to existing modified channels to evaluate possible improvements to instream and riparian habitat. The purpose of this management measure is to correct or prevent detrimental changes to instream and riparian habitat from the impacts of channelization and channel modification projects.

Implementation of this management measure should begin during the planning process for new projects. For existing projects, implementation of this management measure can be included as part of a regular operation and maintenance program. The approach is two-pronged and should include:

1. *Planning and evaluation*, with numerical models for some situations, of the types of NPS pollution related to instream and riparian habitat changes and watershed development.
2. *Operation and maintenance* activities that restore habitat through the application of a combination of nonstructural and structural practices to address some types of NPS problems stemming from instream and riparian habitat changes or watershed development.

B. Practices for Planning and Evaluation

Several tools can be used to evaluate the instream and riparian health of a stream system. These approaches include:

- Biological methods/models
- Temperature measures
- Geomorphic assessment techniques
- Expert judgment and checklists

> *Use models/methodologies to evaluate the effects of proposed channelization and channel modification projects on instream and riparian habitat and to determine the effects after such projects are implemented.*

Biological Methods/Models

To assess the biological impacts of channelization, it is necessary to evaluate both physical and biological attributes of the stream system. Assessment studies should be performed before and after channel modification, with samples being collected upstream from, within, and downstream from the modified reach to allow characterization of baseline conditions. It is also desirable to identify and sample a reference site within the same ecoregion as part of the rapid bioassessment procedures discussed below.

There are a number of different methods that can be used to assess the biological impacts of channelization. Rapid Bioassessment Protocols (RBPs) were developed as inexpensive screening tools for determining whether a stream is supporting a designated aquatic life use (Plafkin et al., 1989; Barbour et al., 1999). One component of these protocols is an instream habitat assessment procedure that measures physical characteristics of the stream reach (Barbour and Stribling, 1991). An assessment of instream habitat quality based on 12 instream habitat parameters is performed in comparison to conditions at a “reference” site, which represents the “best attainable” instream habitat in nearby streams similar to the one being studied. The RBP habitat assessment procedure has been used in a number of locations across the United States. A field crew of one person typically can perform the procedure in approximately 20 minutes per sampling site.

Rapid Bioassessment Protocols (Plafkin et al., 1989; Barbour et al., 1999) were designed to be scientifically valid and cost-effective and to offer rapid return of results and assessments. Protocol III (RBP III) focuses on quantitative sampling of benthic macroinvertebrates in riffle/run habitat or on other submerged, fixed structures (e.g., boulders, logs, bridge abutments, etc.) where such riffles may not be available. The data collected are used to calculate various metrics pertaining to benthic community structure, community balance, and functional feeding groups. The metrics are assigned scores and compared to biological conditions as described by either an ecoregional reference database or site-specific reference sites chosen to represent the “best attainable” biological community in similarly sized streams. In conjunction with the instream habitat quality assessment, an overall assessment of the biological and instream habitat quality at the site is derived. RBP III can be used to determine spatial and temporal differences in the modified stream reach. Application of RBP III requires a crew of two persons; field collections and lab processing require 4 to 7 hours per station and data analysis about 3 to 5 hours, totaling 7 to 12 hours per station. The RBP III has been extensively applied across the United States.

Karr et al. (1986) describes an Index of Biological Integrity (IBI), which includes 12 metrics in three major categories of fish assemblage attributes: species composition, trophic composition, and fish abundance and condition. Data are collected at each site and compared to those collected at regional reference sites with relatively unimpacted biological conditions. A numerical rating is assigned to each metric based on its degree of agreement with expectations of biological condition provided by the reference sites. The sum of the metric ratings yields an overall score for the site. Application of the IBI requires a crew of two persons; field collections require 2 to 15 hours per station and data analysis about 1 to 2 hours, totaling 3 to 17 hours per station. The IBI, which was originally developed for midwestern streams, can be readily adapted for use in other regions. It has been used in several states across the country to assess a wide range of impacts in streams and rivers.

Habitat Evaluation Procedures (HEPs) can be used to document the quality and quantity of available habitat, including aquatic habitat, for selected wildlife species. HEPs provide information for two general types of instream and riparian habitat comparisons:

- The relative value of different areas at the same point in time
- The relative value of the same area at future points in time

By combining the two types of comparisons, the impact of proposed or anticipated land and water use changes on instream and riparian habitat can be quantified (Ashley and Berger, 1997).

Additional information about the assessment methods discussed above, as well as other methods for assessing biological impacts is available in Table 1.5.

Table 1.5 Models and Assessment Approaches

Model or Assessment Approach	Description	Model Resources
Index of Biological Integrity (IBI)	An aquatic ecosystem health index using measures of total native fish species composition, indicator species composition, pollutant intolerant and tolerant species composition, and fish condition.	Reference: Ohio EPA. 1987. *Biological Criteria for the Protection of Aquatic Life*. Vol 1-3. Ohio Environmental Protection Agency, Columbus Ohio. Available online at: http://www.epa.state.oh.us/dsw/bioassess/BioCriteriaProtAqLife.html
Invertebrate Community Index (ICI)	An invertebrate community health index using ten structural and compositional invertebrate community metrics including number of mayfly, caddisfly, and dipteran taxa.	Reference: Ohio EPA. 1987. *Biological Criteria for the Protection of Aquatic Life*. Vol 1-3. Available online at: http://www.epa.state.oh.us/dsw/bioassess/BioCriteriaProtAqLife.html
(Modified) Index of Well-Being (IWB)	The IWB is a fish community health index using measures of fish species abundance and diversity estimates. The *modified* index of well being factors out 13 pollutant tolerant species of fish from certain calculations to prevent false high readings on polluted streams which have large populations of pollutant tolerant fish.	Reference: Ohio EPA. 1987. *Biological Criteria for the Protection of Aquatic Life*. Vol 1-3. Available online at: http://www.epa.state.oh.us/dsw/bioassess/BioCriteriaProtAqLife.html
Instream Flow Incremental Methodology (IFIM)	A river network analysis that incorporates fish habitat, recreational opportunity, and woody vegetation responses to alternative water management schemes. Information is presented as a time series of flow and habitat at select points within the network.	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/ifim/ifim.asp
Physical Habitat Simulation Model (PHABSIM)	A set of computer programs designed to predict the microhabitat (depth, velocities, channel indices) conditions in rivers at different flow levels and the relative suitability of those conditions for different life stages of aquatic life. (Serves as the key microhabitat simulation component of IFIM.)	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/phabsim/phabsim.asp

Model or Assessment Approach	Description	Model Resources
Salmonid Population Model (SALMOD)	A computer model that simulates the dynamics (spawning, growth, movement, and mortality) of freshwater salmonid populations, both anadromous and resident, under various habitat quality and capacities.	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/salmod/salmod.asp
Stream Network/Stream Segment Temperature Models (SNTEMP/SSTEMP)	Developed to help predict the consequences of stream manipulation on water temperatures, these computer models simulate mean daily water temperatures for streams and rivers from data describing the stream's geometry, meteorology, and hydrology. SNTEMP is for a stream network with multiple tributaries for multiple time periods. SSTEMP is a scaled down version suitable for single (to a few) reaches and single (to a few) time periods.	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/SNTEMP/SNTEMP.asp
Systems Impact Assessment Model (SIAM)	An integrated set of models used to aid the evaluation of water management alternatives, it address significant interrelationships among selected physical (temperature, microhabitat), chemical (dissolved oxygen, water temperature) and biological variables (young-of-year Chinook salmon production), and stream flow. Developed for the Klamath River in northern California.	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/siam/siam.asp
Time-Series Library (TSLIB)	A set of DOS-based computer programs to create monthly or daily habitat time-series and habitat-duration curves using the habitat-discharge relationship produced by PHABSIM. (Can serve as the hydraulic component of IFIM).	For more information, visit the USGS Web site: http://www.mesc.usgs.gov/products/software/tslib/tslib.asp
Habitat Evaluation Procedures/Habitat Suitability Index (HEP/HSI)	HEP is an evaluation method that determines the suitability of available habitat for select aquatic and terrestrial wildlife species and measures the impact of proposed land or water use changes on that habitat. HSI is a measure of habitat suitability.	For more information, visit the USFWS Web site: http://policy.fws.gov/870fw1.html, and the USGS Web sites: http://www.mesc.usgs.gov/products/software/hep/hep.asp and http://www.mesc.usgs.gov/products/software/hsin/hsin.asp

Model or Assessment Approach	Description	Model Resources
Rapid Stream Assessment Technique (RSAT)	A reference stream/integrated ranking approach to evaluate steam health based on chemical stability, channel scouring/sediment deposition, physical instream habitat, water quality, riparian habitat, and biological indicators.	Reference: Center for Watershed Protection. 1998. *Rapid Watershed Planning Handbook: A Comprehensive Guide for Managing Urbanizing Watersheds*. Center for Watershed Protection, Ellicott City, MD. For a copy contact: The Center for Watershed Protection, 8391 Main Street Ellicott City, MD 21043, email: center@cwp.org. For more information, visit the Center for Watershed Protection Stormwater Manager's Resource Center: http://www.stormwatercenter.net (Navigate to Monitor/Assess)
Rapid Channel Assessment (RCA)	A reference stream/integrated ranking approach to evaluate the physical condition of a stream channel based on channel geometry, percent channel-bank scour, sediment size distribution and embeddedness, large wood debris, and thalweg profiles.	Reference: Center for Watershed Protection. 1998. *Rapid Watershed Planning Handbook: A Comprehensive Guide for Managing Urbanizing Watersheds*. Center for Watershed Protection, Ellicott City, MD. For a copy contact: The Center for Watershed Protection, 8391 Main Street Ellicott City, MD 21043, email: center@cwp.org.
Rapid Bioassessment Protocols (RBP)	A set of protocols that offer cost-effective techniques of varying complexity to characterize the biological integrity of streams and rivers using the collection and analysis of biological, physical and chemical data. It focuses on periphyton, benthic macroinvertebrates and fish assemblages, and on assessing the quality of the physical habitat.	For more information, visit the EPA Web site: http://www.epa.gov/owow/monitoring/rbp/
Rosgen's Stream Classification Method	A classification method that uses morphological stream characteristics to organize streams into relatively homogeneous stream types to predict stream behavior and to apply interpretive information.	Reference: Rosgen, D. 1996. *Applied River Morphology*. Wildland Hydrology, Pagosa Springs, CO. For a copy contact: Wildland Hydrology Books, 1481 Stevens Lake Road, Pagosa Springs, CO 81147.

Model or Assessment Approach	Description	Model Resources
EPA Volunteer Stream Monitoring Methods	A series of methods geared for volunteer monitoring programs offering simple to advanced techniques for monitoring macroinvertebrates, habitat, water quality, and physical conditions.	For more information, visit the EPA Web site: http://www.epa.gov/owow/monitoring/volunteer/stream/
AQUATOX	A freshwater ecosystem simulation model designed to predict the fate of various pollutants such as nutrients and organic toxicants and their effects on the ecosystem, including fish, invertebrates, and aquatic plants (including periphyton).	For more information, visit the EPA Web site: http://epa.gov/waterscience/models/aquatox
Riverine Community Habitat Assessment and Restoration Concept (RCHARC)	A simulation approach using computer models to compare hydraulic conditions and microhabitats of a reference reach to alternative study reach(es).	Reference: Nestler, J., T. Schneider, and D. Latka. 1993. RCHARC: A new method for physical habitat analysis. *Engineering Hydrology*, 294-99.
Stream Visual Assessment Protocol (SVAP)	A simple procedure to evaluate the condition of a stream based on visual characteristics. It also identifies opportunities to enhance biological value and conveys information on how streams function.	For more information, visit the NRCS Web site: http://www.wcc.nrcs.usda.gov/wqam/wqam-docs.html (Navigate to Stream Visual Assessment Protocol)
A Procedure to Estimate the Response of Aquatic Systems to Changes in Phosphorus and Nitrogen Inputs	A simple tool to estimate the responsiveness of a waterbody to changes in the loading of phosphorus and nitrogen using a dichotomous key that classifies it according to key characteristics.	For more information, visit the NRCS Web site: http://www.wcc.nrcs.usda.gov/wqam/wqam-docs.html (Navigate to A Procedure to Estimate the Response of Aquatic Systems to Changes in Phosphorus and Nitrogen Inputs)
HEC-RAS, River Analysis System, Version 3.1.2	The HEC-RAS system is used to calculate water surface profiles for both steady and unsteady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach.	For more information, visit the USACE Hydrologic Engineering Center Web site: http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html and NRCS Web site: http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-hec-ras.html

Model or Assessment Approach	Description	Model Resources
HEC-HMS, Hydrologic Modeling System, Version 2.2.2	A system designed to simulate the precipitation-runoff processes of dendritic watershed systems. In addition to unit hydrograph and hydrologic routing options, capabilities include a linear quasi-distributed runoff transform (ModClark) for use with gridded precipitation, continuous simulation with either a one-layer or more complex five-layer soil moisture method, and a versatile parameter estimation option.	For more information, visit the USACE Hydrologic Engineering Center Web site: http://www.hec.usace.army.mil/software/hec-hms/hechms-hechms.html
TR-55, Urban Hydrology for Small Watersheds	Simplified procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes required for floodwater reservoirs.	For more information, visit the NRCS Web site: http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr55.html
TR-20, Computer Program for Project Formulation Hydrology	A physically based watershed scale runoff event model that computes direct runoff and develops hydrographs resulting from any synthetic or natural rainstorm. Developed hydrographs are routed through stream and valley reaches as well as through reservoirs.	For more information, visit the NRCS Web site: http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-wintr20.html
QUAL2K	A modernized version of QUAL2E, a model that simulates the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the dissolved oxygen balance.	For more information, visit the EPA Web site: http://www.epa.gov/athens/wwqtsc/html/qual2k.html
Cornell Mixing Zone Expert System (CORMIX)	A water quality modeling and decision support system designed for environmental impact assessment of mixing zones resulting from wastewater discharge from point sources. The system emphasizes the role of boundary interaction to predict plume geometry and dilution in relation to regulatory mixing zone requirements.	For more information, visit the EPA Web site: http://www.epa.gov/waterscience/models/cormix.html

Model or Assessment Approach	Description	Model Resources
RiverWare™	RiverWare™ is a reservoir and river modeling software decision support tool. With RiverWare™, users can model the topology, physical processes and operating policies of river and reservoir systems, and make better decisions about how to operate these systems by understanding and evaluating the trade-offs among the various management objectives. Water management professionals can improve their management of river and reservoir systems by using the software. The Bureau of Reclamation, the Tennessee Valley Authority, and the Army Corps of Engineers sponsor ongoing RiverWare™ research and development.	For more information, visit the Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES) Web site: http://cadswes.colorado.edu/riverware/

Temperature Measures

Channelization and channel modification activities can greatly impact stream temperature. When a channel is narrowed, the water depth increases and the surface area exposed to solar radiation and ambient temperature decreases. This can decrease water temperature. When a channel is widened, the opposite occurs; shallower depths and increased temperatures occur. Temperature may also be increased from increased turbidity because the sediment particles absorb heat. As a result, it is important to model how temperature will change in a stream, as a result of channelization and channel modification activities, to determine what other changes and impacts might occur in the stream.

Stream temperature has been widely studied, and heat transfer is one of the better-understood processes in natural watershed systems. Most available approaches use energy balance formulations based on the physical processes of heat transfer to describe and predict changes in stream temperature. The six primary processes that transfer energy in the stream environment are:

1. Short-wave solar radiation
2. Long-wave solar radiation
3. Convection with the air
4. Evaporation
5. Conduction to the soil
6. Advection from incoming water sources (e.g., ground-water seepage)

Several computer models that predict instream water temperature are currently available. These models vary in the complexity of detail with which site characteristics, including meteorology, hydrology, stream geometry, and riparian vegetation, are described. The U.S. Fish and Wildlife Service developed an instream surface water temperature model (Theurer et al., 1984) to predict mean daily temperature and diurnal fluctuations in surface water temperatures throughout a stream system. The model, Stream Network Temperature Model (SNTEMP), can be applied to any size watershed or river system. This predictive model uses either historical or synthetic hydrological, meteorological, and stream geometry characteristics to describe the ambient conditions. The purpose of the model is to predict the longitudinal temperature and its temporal variations. The instream surface water temperature model has been used satisfactorily to evaluate the impacts of riparian vegetation, reservoir releases, and stream withdrawal and returns on surface water temperature. In the Upper Colorado River Basin, the model was used to study the impact of temperature on endangered species (Theurer et al., 1982). It also has been used in smaller ungauged watersheds to study the impacts of riparian vegetation on salmonid habitat. For more information or to download SNTEMP, see the U.S. Geological Survey web site: http://www.mesc.usgs.gov/products/software/SNTEMP/sntemp.asp.

The Stream Segment Temperature Model (SSTEMP) is a much-scaled down version of the SNTEMP model developed by the USGS Biological Resource Division. Unlike the large network model (SNTEMP), this program only handles single stream segments for a single time period (e.g., month, week, day) for any given "run." Initially designed as a training tool, SSTEMP may be used satisfactorily for a variety of simple cases that one might face on a day-today basis. It is especially useful to perform sensitivity and uncertainty analysis. The model predicts minimum 24-hour temperatures, mean 24-hour temperatures, and maximum 24-hour stream temperatures for a given day, as well as a variety of intermediate values. The SSTEMP model identifies current stream and/or watershed characteristics that control stream temperatures. The model also quantifies the maximum loading capacity of the stream to meet water quality standards for temperature. This model is important for estimating the effect of changing controls or factors (such as riparian grazing, stream channel alteration, and reduced streamflow) on stream temperature. The model can also be used to help identify possible implementation activities to improve stream temperature by targeting those factors causing impairment to the stream. Good input data and an awareness of the model's assumptions are critical to obtaining reliable predictions. SSTEMP may be used to evaluate alternative reservoir release proposals, analyze the effects of changing riparian shade or the physical features of a stream, and examine the effects of different withdrawals and returns on instream temperature. More information about the model is available on the U.S. Geological Survey web site: http://www.mesc.usgs.gov/products/software/software.asp (navigate to Stream Network Temperature Model and Stream Segment Temperature Model).

Case Study: New Mexico Uses Temperature Models for TMDL Development

The State of New Mexico has been using the Stream Segment Temperature (SSTEMP) model for the development of Total Maximum Daily Load (TMDL) documents for temperature impaired waterbodies. SSTEMP version 1.2.2 was used to predict stream temperatures based on watershed geometry, hydrology, meteorology and stream shading.

In 1999, SSTEMP was utilized in preparing the TMDL for North Ponil Creek, a waterbody impaired due to exceedances of New Mexico's water quality standards for temperature. The SSTEMP model was used to predict the 24-hour minimum, mean, and maximum daily water temperature. This helped to determine the need for increased stream shading and to develop the potential BMPs of 1) riparian revegetation and 2) riparian fencing to reduce damage to riparian vegetation.

Sources:
Bartholow, J. (USGS) 1999. *Stream Segment Temperature Model (SSTEMP) Version 1.0.0* http://www.fort.usgs.gov/products/Publications/4041/4041.pdf. Accessed July 2003.

New Mexico Environment Department. 2002. Surface Water Quality Bureau. Personal Communication with Lynette Stevens. 12/12/02 email to Kristen Dors.

Total Maximum Daily Load for Temperature on North Ponil Creek. 1999. http://www.epa.gov/owow/tmdl/examples/temperature/nm_northponiltemp.pdf. Accessed July 2003.

Geomorphic Assessment Techniques

Fluvial geomorphology is the study of stream form and function. Geomorphic assessment focuses on qualitative and quantitative observations of stream form. It provides a "moment-in-time" characterization of the existing morphology of the stream. In addition, geomorphic assessment includes a stability component. Stability assessments place the stream in the context of past, present, and anticipated adjustment processes. Geomorphic assessments can be useful in predicting changes that could be created by channelization and channel modification activities.

Stream classification is a technique that is used to show the relationship between streams and their watersheds. There are several techniques for stream classification, all of which have advantages and limitations. Advantages of geomorphic assessment include (adapted from FISRWG, 1998):

- Promotes communication
- Enables extrapolation of data collected on a few streams to a number of channels over a broader geographical area.
- Helps the restoration practitioner consider the landscape context and determine expected ranges of parameters.
- Enables practitioners to interpret the channel-forming or dominant processes active at the site.
- Reference reaches can be used as the desired outcome of restoration.
- Provides an important cross-check to verify if the selected design values are within a reasonable range.

Limitations of geomorphic assessment include (adapted from FISRWG, 1998):

- Determination of bankfull or channel-forming flow depth may be difficult or inaccurate.
- The dynamic condition or the stream is not indicated in stream classification systems.
- River response to a perturbation or restoration action is normally not determined by classifying it alone.
- Biological health is not directly determined.
- Classifying a stream should not be used alone to determine the type, location, and purpose of restoration activities.

Four geomorphic assessment techniques that are discussed in this document are the following:

- Schumm
- Montgomery and Buffington
- Channel Evolution Model (CEM)
- Rosgen

Schumm identified straight, meandering, and braided channels and related both channel pattern and stability to modes of sediment transport. Schumm recognized that stable straight and meandering channels have mostly suspended sediment loads and cohesive bank materials, as opposed to unstable braided streams characterized by mostly bedload sediment transport and wide sandy channels with noncohesive bank materials. Meandering mixed-load channels are found at an intermediate condition (FISRWG, 1998).

Montgomery and Buffington proposed a classification system similar to Schumm for alluvial, colluvial, and bedrock streams in the Pacific Northwest. This system addresses channel response to sediment inputs throughout the drainage network. Six classes of alluvial channels were identified – cascade, step-pool, plane-bed, riffle-pool, regime, and braided. The stream types are differentiated based on channel response to sediment inputs. For example, steeper channels maintain their morphology while transporting sediment, while streams with lower gradients make more morphological adjustments with increased sediment loads (FISRWG, 1998).

A conceptual model of channel evolution in response to channelization (CEM-channel evolution model) has been developed by Simon and Hupp (1986, 1987), Hupp and Simon (1986, 1991), and Simon (1989a, 1989b). The model identifies six geomorphic stages of channel response and was developed and extensively applied to predict empirical stream channel changes following large-scale channelization projects in western Tennessee. Data required for model application include bed elevation and gradient, channel top-width, and channel length before, during, and after modification. Gauging station data can be used to evaluate changes through time of the stage-discharge relationship and bed-level trends. Riparian vegetation is dated to provide ages of various geomorphic surfaces and thereby to deduce the temporal stability of a reach.

A component of Simon and Hupp's (1986, 1987) channel response model is the identification of specific groups of woody plants associated with each of the six geomorphic channel response stages. Their findings for western Tennessee streams suggest that the site preference or avoidance patterns of selected tree species allow their use as indicators of specific bank conditions. This method might require calibration for specific regions of the United States to account for differences in riparian zone plant communities, but it would allow simple vegetative reconnaissance of an area to be used for a preliminary estimate of stream recovery stage (Simon and Hupp, 1987).

Restoring or maintaining streams to a stable form through natural channel design requires detailed information about surface water hydrology and the interactions between rainfall and overland flow or runoff. The Rosgen classification system, developed by David L. Rosgen, and presented in *Applied Fluvial Geomorphology*, is the most comprehensive and widely used quantitative assessment method for geomorphology. It represents a compilation of much of the early work in applied fluvial geomorphology and relies largely on the identification of bankfull field indicators. The bankfull discharge is the flow event that fills a stable alluvial channel up to the elevation of the active floodplain. Dunne and Leopold (1978) first developed hydraulic geometry relationships for the bankfull stage, also called regional curves. Most river engineers and hydrologists work under the assumption that the bankfull discharge is equivalent to the channel forming or dominant discharge in geomorphic classification and in analog and empirical design methods. The bankfull discharge is the only discharge that can be identified in the field using physical indicators, therefore it is one of the most commonly used in natural channel design.

Moment-in-time stream classifications provide insights into the existing form of the stream and can help to define design parameters and understand potential modifications in reference to existing conditions. Stream classification offers a way to categorize streams based on channel morphology. The older classification systems were largely qualitative descriptions of stream features and landforms and were difficult to apply universally. In 1994, Rosgen published *A Classification of Natural Rivers*. Because of its usefulness in stream restoration, the Rosgen classification system has become popular among hydrologists, engineers, geomorphologists, and biologists working to restore the biological function and stability of degraded streams. The classification produces 41 major stream types for which stream channel stability and stream bank erosion potential can be assessed. From the assessment, structures for in-stream and stream bank restoration or modification can be selected.

Classification of the current status of a stream provides the following benefits:

- Allows for effective communications between various disciplines, such as geologists, hydrologists, and biologists working on stream management or restoration.
- Provides a consistent, replicable platform for integration of various stream resource inventories and assessments.
- Assists with predictions of future stream behavior based on local knowledge of how different stream types respond to change.

In addition to stream classification, assessment of stream stability greatly improves decision making in regard to potential stream modifications. Rosgen's stream channel stability method provides a sequence of steps for the field practitioner to use in reaching final conclusions and making recommendations for management, stream design, or restoration. The field practitioner uses field-measured variables to assess:

- Stream state or channel condition variables
- Vertical stability (degradation/aggradation)
- Lateral stability
- Channel patterns
- Stream profile and bed features
- Channel dimension factor
- Channel scour/deposition (with competence calculations of field verified critical dimensionless shear stress and change in bed and bar material size distribution)
- Stability ratings adjusted by stream type
- Dimensionless ratio sediment rating curves by stream type and stability ratings
- Selection of position in stream type evolutionary scenario as quantified by morphological variables by stream type to determine state and potential of stream reach.

The stability assessment is conducted on a reference reach and a departure analysis is performed when compared to an unstable reach of the same stream type. Changes in the variables controlling river channel form, primarily streamflow, sediment regime, riparian vegetation, and direct physical modifications can cause stream channel instability. Separating the differences between anthropogenic versus geologic processes in channel adjustment is a key to prevention, mitigation, and restoration of disturbed systems.

Rosgen has created a river inventory hierarchy involving four levels that would allow a stream assessment to be conducted at various levels, ranging from broad qualitative descriptions to detailed quantitative descriptions. The idea is to provide documented measurements, coupled with consistent, quantitative indices of stability to make the approach to stream assessments less subjective and more consistent and reproducible. Level I and Level II are used to do the initial stratification of a reach by valley and stream type. Level III is used to predict stability. Level IV is used for validation, and requires the greatest amount of detail over a longer time period. For example, vertical stability and bank erosion can be estimated at Level III. But, in a Level IV assessment, permanent cross-sections are revisited over time to verify shifts in bed elevation and measure actual erosion that occurred.

The four hierarchal levels, and the measurements and determinations they include, are shown below along with their objectives.

Level I – Geomorphic characterization: Used to describe generalized fluvial features using remote sensing and existing inventories of geology, landform evolution, valley morphology, depositional history and associated river slopes, relief and patterns utilized for generalized categories of major stream types and associated interpretations.

Level II – Morphological description: To delineate homogeneous stream types that describe specific slopes, channel materials, dimensions and patterns from reference reach measurements and provide a more detailed level of interpretation than Level I. Includes measurements such as sinuosity, width/depth ration, slope, entrenchment ratio, and channel patterns and material.

Level III – Stream "state" or condition: The "state" of streams further describes existing conditions that influence the response of channels to imposed change and provide specific information for prediction methodologies (such as stream bank erosion calculations). Provides for very detailed descriptions and associated interpretation and predictions. Includes such measurements and/or characterizations of vegetation, deposition, debris, meander patterns, channel stability index, and flow regime.

Level IV – Reach specific studies (validation level): Provides reach-specific information on channel processes. Used to evaluate prediction methodologies; to provide sediment, hydraulic and biological information related to specific stream types; and to evaluate effectiveness of mitigation and impact assessments for activities by stream type. Involves direct measurements of sediment transport, bank erosion rates, aggradation/degradation, hydraulics, and biological data.

Rosgen's stream classification methodologies can assist in stream design by:

- Enabling more precise estimates of quantitative hydraulic relationships associated with specific stream and valley morphologies.
- Establishing guidelines for selecting stable stream types for a range of dimensions, patterns, and profiles that are in balance with the river's valley slope, valley confinement, depositional materials, streamflow, and sediment regime of the watershed.
- Providing a method for extrapolating hydraulic parameters and developing empirical relationships for use in the resistance equations and hydraulic geometry equations needed for restoration design.
- Developing a series of meander geometry relationships that are uniquely related to stream types and their bankfull dimensions.
- Identifying the stable characteristics for a given stream type by comparing the stable form to its unstable or disequilibrium condition.

Refer to *Applied River Morphology* (Rosgen, 1996) for more information on this stream classification system and potential applications.

The methods and techniques used to accomplish a geomorphic assessment should be project-specific and conducted by personnel trained in applied fluvial geomorphology. The key is that the geomorphic assessment must provide a fundamental understanding of the linkage between river form and process. The assessment should provide insight into where the stream has been, is now, and in what direction it is moving. It should also place the project reach in the context of broader system wide adjustment processes. Geomorphic assessment can be used to select sites for restoration and perform designs.

In site selection, geomorphic assessments can determine if a site is unstable, and in need of some form of restoration activity. During design, geomorphic assessments can be used in combination with hydrologic, hydraulic, and/or sediment transport analyses to define design elements such as channel slope and hydraulic geometry.

Case Study: Sugar Creek Watershed

Sugar Creek Watershed, located primarily in Caddo County, Oklahoma, lies in the Western Sandstone Hills, and drains approximately 233 square miles (148,748 acres) into the Washita River. Sugar Creek's headwaters originate 3 miles west of Hinton, Oklahoma and flow in a south-southeasterly direction for about 31 miles. In the early 1900s, before settlement, Sugar Creek's stability was governed by the valley, a wide shallow floodplain, prairie grasses, and trees. As the watershed was settled, land use changed, cropland replaced grasslands, and woodlands were cleared. Sugar Creek's tributaries were pushed over to the edges of plowed fields. This resulted in increased runoff and detachment of upland sediments. Consequently, Sugar Creek's lower reaches and floodplains aggraded and frequent flooding occurred, with 100 floods recorded from 1923 to 1949. In the late 1950s, the South Caddo County Soil and Water District and North Caddo County Soil Conservation District requested that the USDA Soil Conservation Service (now USDA NRCS) initiate a watershed protection project to reduce flooding and address sedimentation. Under the Flood Control Act of 1944, Sugar Creek Watershed was one of eleven projects authorized. Planned measures included 43 flood-retarding structures, 21.3 miles of channel improvement, several grade stabilization structures, and other land treatment measures.

Since Sugar Creek channel was first constructed in the mid 1960s, flooding has been significantly reduced or eliminated. However, there have been continual problems with channel grade degradation, bank instability, and sedimentation. Although there have been many attempts to stabilize various reaches of the channel, only some have met with limited success. The four primary problems that exist in the Sugar Creek Watershed today include 1) sedimentation in the Washita River downstream from the confluence with Sugar Creek; 2) bank instability along Sugar Creek's main channel and tributaries; 3) degrading side lateral channels; and 4) possible excessive sedimentation in some of the floodwater retarding structures.

Sugar Creek's drainage network is not functioning as designed due to excessive erosion and stabilization problems. A geomorphic study of streams in the watershed was initiated to assess erosion in the system and determine alternative methods to stabilize the main channel and primary tributaries. A major component of the study was the development of a good classification scheme, which should 1) simplify a complex drainage network into understandable pieces; 2) categorize stream types based on reproducible parameters measured in the field; 3) uphold channel evolution models as verified through observation of similar, but "aged" stream reaches; and 4) facilitate a methodology to assess present and potential future conditions among varied reaches. For Sugar Creek, David Rosgen's Classification System was chosen to describe, express, and relate the reaches' present state and characteristics. The Rosgen classification system also lends itself to predicting the streams future evolutionary stage. By combining field measurements before and after past channelization projects in Sugar Creek with Rosgen's methodology, NRCS staff were able to evaluate the impacts of the projects on stream channel stability. Rosgen's methodology accurately predicts aggradation of the stream channel resulting from channel straightening that increased the energy gradient with respect to bed slope.

The geomorphic study and restoration principles for Sugar Creek is being used in conjunction with a strategy to implement restoration projects on critical areas, which will most likely reduce excessive sedimentation, increase wildlife habitat, increase water quality, and reduce instability to the rest of Sugar Creek's main stem and tributary reaches. Goals of the restoration include 1) protect the existing infrastructure (roads and flood retarding structures) from headcut undercutting; 2) arrest upstream migration of headcuts in the tributaries and subsequent channel widening; 3) strengthen/protect channel banks and reduce the rate of meander migration; 4) improve habitat along riparian corridors; 5) minimize operation and maintenance costs; and 6) maintain flood protection.

Additional information about Sugar Creek and the restoration study is available at: http://wmc.ar.nrcs.usda.gov/technical/HHSWR/Sugarcreek/sugarcreek.html.

Source:
NRCS. No date. *Sugar Creek Fluvial Geomorphic Restoration Study*. http://wmc.ar.nrcs.usda.gov/technical/HHSWR/Sugarcreek/sugarcreek.html. Accessed December 2004.

Sediment transport analysis in rivers and streams is used to approximate the amount of sediment being moved by flow event scenarios and to determine where it will be deposited. Modeling the sediment transport capacity of a channel and its predicted sediment deposition patterns are important for assessing existing and proposed channel design projects to estimate potential project impacts. Sediment transport analysis is also useful for determining restoration opportunities in existing channelization and channel modification projects. Sediment transport analysis is often coupled with stable channel analyses methods to refine channel geometries to estimate optimal scour and deposition characteristics (Schulte et al., 2000). A good source of technical information on sediment transport analysis can be found in *River Engineering for Highway Encroachments* (FHWA, 2001).

Sediment transport analysis has been used in many projects, including:

- Channel design projects (Schulte et al., 2000)
- Stream restoration design (Shields et al., 2003 and Copeland et al., 2001)
- Flood control projects (USACE, 1994)
- Highway projects that include stream crossings (FHWA, 2001)

In the design of new channelization projects and analysis of existing projects, channels are typically evaluated using channel stability methods and then the analysis is refined using sediment transport models. Sediment transport analysis is used to refine geometry so that scour and deposition are minimized. It is also used to determine the optimum grade control structure elevation and placement and to find the excavation depths in depositional zones to minimize operational costs for maintaining the channel geometry (Schulte et al., 2000).

Expert Judgment and Checklists

Approaches using expert judgment and checklists developed based on experience acquired in previous projects and case studies may be very helpful in integrating environmental goals into project development. The USACE used this concept of incorporating environmental goals into project design (Shields and Schaefer, 1990) in the development of a computer-based system for the environmental design of waterways (ENDOW). The ENDOW system is composed of three modules: streambank protection module, flood control channel module, and streamside levee module. The three modules require the definition of the pertinent environmental goals to be considered in the identification of design features. Depending on the environmental goals selected for each module, ENDOW will display a list of comments or cautions about anticipated impacts and other precautions to be taken into account in the design.

Another example of using expert judgment is the Proper Functioning Condition (PFC) technique. PFC was developed by the Bureau of Land Management (BLM) to rapidly assess whether a stream riparian area is functioning properly in terms of hydrology, landform/soils, channel characteristics, and vegetation. The assessment is performed by an interdisciplinary team and involves completing a checklist evaluating 17 factors concerning hydrology, vegetation, and erosional/depositional characteristics. The PFC field technique is not quantitative, but with adequate training, results are reproducible to a high degree (FISRWG, 1998).

C. Practices for Operation and Maintenance

Implementation practices for instream and riparian habitat restoration in planned or existing modified channels are consistent with those management practices for physical and chemical characteristics of channelized or modified surface waters. To prevent future impacts to instream or riparian habitat or to solve current problems caused by channelization or channel modification projects, include one or more of the following practices to mitigate the undesirable changes.

- Streambank protection
- Levees
- Setback levees and floodwalls
- Grade control structures
- Vegetative cover
- Instream sediment load controls
- Noneroding roadways

Operation and maintenance programs should weigh the benefits of including practices such as these for mitigating any current or future impairments to instream or riparian habitat. Additional information about these practices can be found in Part C (Practices for Operation and Maintenance) on page 1-27 above and in Section 3 of this document. Also, Fischenich and Allen (2000) is a comprehensive summary of practices that can be evaluated for use in operation and maintenance programs.

Identifying Opportunities for Restoration

Ensuring the involvement and participation of all partners is a place to start on the road to restoration. Determining the extent of the restoration activity is can help identify potential partners and other interested stakeholders. Each stakeholder may bring a certain expertise, historical information and data, and possibly funding to a project. Development of a stream corridor restoration plan can help organize the group, set goals for implementation of management practices, secure funding or other types of support, and facilitate the sharing of ideas and accomplishments within the group and to others in the community.

Section 2 Dams

Introduction

Dams are a common form of hydromodification. The National Research Council estimated that there were more than 2.5 million dams in the United States in 1993. Dams generally were built to store and provide water for mechanical power generation (e.g., waterwheels to mill grain), industrial cooling, hydroelectric power generation, agricultural irrigation, municipal water supplies for human consumption, and impoundment-based recreation, such as boating and sport fishing. Dams are also used for flood control and maintaining channel depths for barge transportation.

Dams can be associated with a number of effects, including changes to hydrology, water quality, habitat, and river morphology. Lakes and reservoirs integrate many processes that take place in their contributing watersheds including processes that contribute energy (heat), sediment, nutrients, and toxic substances. Human activities, such as agricultural and urban land use, contribute to contaminant and sediment loads to reservoirs. The presence and operation of dams can determine the fate of these pollutants in a reservoir or impoundment. For example, the presence of a dam may lead to sediment accumulation in a reservoir. However, there are management practices that can be used to mitigate this integrative effect of a reservoir. One example is selective withdrawals, which are an operational technique that can be used by dam operators to provide water quality and temperatures necessary to sustain downstream fish populations.

When dams are built, they alter the structure of a river system, causing it to change from a river (flowing) to lake (static) and back to a river (flowing) system. This alteration can change the flow patterns of the system, which can affect water quality and habitat upstream and downstream of the dam. However, most effects from dams are manifested downstream. Table 2.1 provides a description of several common types, or classes, of dams and some of the possible associated NPS impacts.

Siting, construction, operation, maintenance, and removal of dams can lead to NPS effects. For example, siting of dams can result in inundation of wetlands, riparian areas, and fastland in areas upstream of the dam. During construction or maintenance, erosion and soil loss occurs. Proper siting and design help prevent areas prone to erosion from being developed. Operation of dams, and the amount of water released by dam operators, can affect downstream areas when flood waters necessary to deliver sediment are restricted, or when controlled releases from dams change the timing, quantity, or quality of downstream flows. Finally, removal of dams can lead to physical and biological changes, such as increased turbidity from redistribution of sediment previously stored behind the dam and displacement of warm-water species that prefer lake-like conditions. A more detailed discussion of water quality impacts, biological and habitat impacts, and physical and chemical changes from dam removal is provided throughout Section 2.

Since the presence and operation of a dam have the potential to cause impacts, periodic assessments of reservoir water quality, watershed activities, and operational practices may provide valuable information for evaluating management strategies. The types and severity of the impacts can serve as an indicator of the frequency and magnitude of the assessments. There are a variety of assessment tools that are available to assist decision-makers in the evaluation of impacts associated with dams. Watershed-related impacts and management activities can be evaluated with a variety of models. EPA supports several models that may be useful for watershed assessments, such as BASINS. More information about EPA-supported watershed assessment tools can be found at http://www.epa.gov/waterscience/wqm.

Reservoir water quality can also be assessed with various models. Table 1-1 in this document provides a list of models that may be used to assess reservoir water quality. Also presented in Table 1-1 are models that could be used to evaluate downstream impacts of dams. The USACE Environmental Laboratory develops and supports several models, such as QUAL2E, Bathtub, and CE-QUAL-RI that can be found at http://el.erdc.usace.army.mil/products.cfm.

Table 2.1 Classes of Dams and Corresponding NPS Significance (USDA, 1979)

Class of Dam	Description	NPS Significance
Run-of-the-River Dam	Usually a low dam, with small hydraulic head, limited storage area, short detention time, and no positive control over impoundment storage. The amount of water released from such a dam depends on the amount of water entering the impoundment from upstream sources.	Sediment, flow alterations, habitat alterations
Excavated Pond	Body of water created by digging a pit in a nearly level area.	Sediment, habitat alterations
Embankment Pond	Body of water created by constructing an embankment or dam across a watercourse. These ponds have a depth of water impounded against the embankment at an emergency spillway elevation of 3 ft or more.	Temperature, sediment, flow alterations, habitat alterations, fish migration barrier
Transitional Dam	Dam characterized by a retention time of about 25 to 200 days and a maximum reservoir depth of 100 to 200 ft. In a transitional dam, outflow temperature is approximately equal to the inflow temperature.	Temperature, sediment loss downstream (stored behind dam), habitat alterations, fish migration barrier

Class of Dam	Description	NPS Significance
Retarding Dam	Dam that temporarily stores floodwater and protects land from flooding.	Sediment, habitat alterations, fish migration barrier
Storage Dam	Typically a high dam with large hydraulic head, long detention time, and a positive control over the volume of water released from the impoundment. Dams constructed for either flood control or hydroelectric power generation are usually of the storage class. These dams typically have a retention time of over 200 days and a reservoir depth of over 100 ft. The outflow temperature is sufficient for cold-water fish, even with warm inflows. Storage dams are used to store surface runoff for farm water supply, irrigation, municipal water supply, fish and wildlife, or recreation or to store sediment.	Temperature, sediment loss downstream (stored behind dam), dissolved oxygen, metals, habitat alterations, fish migration barrier
Earth Dam	An earthen embankment constructed across a watercourse with adequate spillways to protect the dam from failure by overtopping caused by flooding from a pre-specified design storm. A design storm is a statistical calculation of the amount of rainfall expected to occur within a given return frequency that generates a flood. Materials used in earth dams are natural and unprocessed. These are the most common dams, and they serve as diversion, storage, grade stabilization, or retarding dams.	Sediment, habitat alterations, fish migration barrier
Diversion Dam	A dam that diverts all or some of the water from a waterway into a different watercourse, an irrigation canal, or a water-spreading system.	Metals (from irrigation return flows), flow alterations, sediment; habitat alterations, fish migration barrier
Grade Stabilization Dam	This type of dam is used to drop water flows from one level to another to stabilize the flow of a waterbody.	Flow alterations, habitat alterations, fish migration barrier

One opportunity to evaluate and address the NPS impacts of some larger dams that are used for hydropower occurs during the licensing/relicensing process. The Federal Power Act (FPA) requires all nonfederal hydropower projects located on navigable waters to be licensed. The Federal Energy Regulatory Commission (FERC) is the independent regulatory agency within the Department of Energy that has exclusive authority, under the FPA, to license such projects. The hydropower dam relicensing process offers an opportunity to assess the balance between natural resources and the generation of electricity and to address some areas that are determined to be problematic. Stakeholders, including dam owners and operators, local governments, environmental groups, and the public, often have different interests to be balanced. Through the FPA and the relicensing process, these varied interests can be evaluated and a balanced outcome can be derived. To ensure that water quality considerations are taken into account, States and authorized Tribes certify that discharges (including those that originate from dams) meet water quality standards under section 401 of the CWA.

The FPA also requires relicensing to be conducted in light of recent laws and regulations that are in effect at the time of renewal. As regulations related to hydropower dams change, it is possible that many dams that were previously licensed and are up for relicensing may no longer be in compliance with current regulatory standards. For example, many dams were built prior to the CWA, which includes regulatory requirements for protecting and maintaining designated uses. Other regulatory requirements that may be evaluated during relicensing include protections for wetlands, aquatic habitat, and endangered species. Additional information about FERC and hydropower licensing/relicensing is available at http://www.ferc.gov.

Case Study: Flow Restoration Below Hydroelectric Facilities: Relicensing Offers Opportunity to Increase Stream Flows

The impacts of hydroelectric development on Vermont streams were documented in a 1988 report titled *Hydropower in Vermont: An Assessment of Environmental Problems and Opportunities*. In this study, artificial regulation of natural stream flows and the lack of adequate minimum stream flows at Vermont dam sites were found to have largely reduced the success of the state's initiatives to restore the beneficial uses and values for which the affected waters are managed. Of the 62 dams studied, slightly more than three-fourths of the hydroelectric facilities were found to be adversely affecting the flows on the streams on which they were located. The substantial advances being made to clean up Vermont's rivers were being thwarted by this flow regulation problem.

Since 1991, Vermont has used the Clean Water Act Section 319 funding to support the Department of Environmental Conservation's (DEC) participation in relicensing hydroelectric projects (under Clean Water Act section 401 authority). In doing so, DEC has developed positions on relicensing applications, influencing the preparation of conditions for future operation of the facilities to support desired multiple uses of the affected waters. Activities have included evaluating the regulation of reservoir levels and downstream flows, as related to the support of recreational uses, aquatic habitat, and aesthetics, as well as erosion of reservoir/impoundment shorelines and downstream riverbanks. Given the technical and social complexities of relicensing, and in spite of several appeal proceedings, numerous accomplishments have been made. Some key accomplishments include:

- Projects occurring in the Passumpsic, Black, and Ottauquechee Rivers (Connecticut River Drainage) were relicensed subject to a "run-of-river conversion," requiring inclusion of special recreation and landscaping plans, bypass flows, and downstream fish passage.
- The Center Rutland Project (Otter Creek, Lake Champlain Drainage) was relicensed after issuance of a water quality certification. The project is now being operated under a new flow management plan that includes spillage to improve bypass habitat, aesthetics, and dissolved oxygen concentrations in Rutland's wastewater management zone. Expected benefits from this nonpoint source implementation strategy include improved aquatic habitat; increased wastewater assimilative capacity; enhanced recreational uses for swimming, fishing, and boating; elevated dissolved oxygen levels; and reduced turbidity and suspended sediment.

Sources:
U.S. Environmental Protection Agency (USEPA). 2002a. *Flow Restoration Below Hydroelectric Facilities: Relicensing Offers Opportunity to Increase Stream Flows.* U.S. Environmental Protection Agency, Section 319 Success Stories, Volume III. http://www.epa.gov/owow/nps/Section319III/VT.htm. Accessed May 2003.

Vermont Department of Environmental Conservation, Water Quality Division. *Hydroelectric Projects*. http://www.vtwaterquality.org/hydrology/htm/hy_sections.htm. Accessed July 2005.

Dams - Impacts on Water Quality

A. Introduction

The physical presence and operation of dams can result in changes in water quality and quantity. As previously noted, dams are associated with a variety of impacts to water quality and habitat. Some of the water quality impacts include changes in erosion, sedimentation, temperature, dissolved gases, and water chemistry. Examples of biological and habitat impacts, which may result from a combination of physical and chemical changes, include loss of habitat for existing or desirable fish, amphibian, and invertebrate species; changes from cold water to warm water species (or inversely, changes from warm water to cold water species); blockage of fish passage; or loss of spawning or necessary habitat.

The impacts associated with dams occur above (upstream) and below (downstream) the dam. Upstream impacts occur primarily in the impoundment/reservoir created by the presence and operation of the dam. The area and depth of the impoundment will determine the extent and complexity of the upstream and downstream impacts. For example, small, low-head dams with little impounded areas will exhibit different impacts than large storage dams. Sedimentation and fish passage issues at the smaller, low-head dam contrasts to sedimentation, temperature, fish passage, flow regulation, and water quality issues that may be associated with the larger storage dam. The existence of the dam and associated impoundment results in much different water quality interactions than those associated with naturally flowing streams or rivers.

Above dams, activities within the watershed can have significant impacts to water quality within impoundments and in releases from dams to downstream areas. Watershed activities, such as agricultural land use, forestry harvesting, or urbanization can lead to changes in water quantity and quality. Agricultural and forestry practices that lead to sediment-laden runoff may result in increased sediment accumulation within an impoundment. Chemicals (e.g., pesticides and nutrients) that are applied on agricultural crops can be carried with sediment in runoff. Increases in urbanization that result in more impervious areas within a watershed often result in dramatic changes in the quantity and timing of runoff flows. These external sources are integrated by the dam and may result in short-and long-term water quality changes within an impoundment and dam releases.

Water quality in reservoirs and releases from dams are closely linked and scrutinized to uses of the water. Often, there are multiple potential users that may have differing quality needs and perceptions. Management of dams includes balancing dam operations, watershed activities, reservoirs, and downstream water and uses. Dortch (1997) provides an excellent assessment on water quality considerations in *Reservoir Management*. Dortch (1997) notes the following about water quality:

- *Temperature* regulates biotic growth rates and life stages and defines fishery habitat (warm, cool, and cold water).
- *Oxygen* sustains aquatic life.
- *Turbidity* affects light transmission and clarity.

- *Nutrient enrichment* is linked to primary productivity (algal growth) and can cause oxygen depletion, poor taste, and odor problems.
- *Organic chemicals and metals* may be toxic and accumulate when bound to sediment that settles in the reservoir.
- *Total dissolved solids* may be problematic for water supplies and other users.
- *Total suspended solids* are a transport mechanism for nutrients and contaminants. Solids may settle in reservoirs and displace water storage volume.
- *pH* regulates many chemical reactions.
- *Dissolved iron, manganese, and sulfide* can accumulate in reservoir hypolimnions that are depleted of oxygen and can cause water quality problems in the reservoir and release water.
- *Pathogens* include bacteria, viruses, and protozoa that can cause public health problems.

Water uses include water supply, flood control, hydropower, navigation, fish and wildlife conservation, and recreation (Dortch, 1997). All of the uses have varying water quality requirements, ranging from almost none for flood control to high quality needs for water supply, fish and wildlife conservation, and recreation.

B. Water Quality Impacts

Dams act as a barrier to the flow of water, as well as to materials being transported by the water. This can impact water quality both in the impoundment/reservoir created by the dam and downstream of the dam. Alteration to the chemical and physical qualities of water held behind a dam is often a function of the retention time of a reservoir or the amount of time the water is retained and not able to flow downstream. Water held in a small basin behind a run-of-river dam may undergo minimal alteration. In contrast, water stored for months or even years behind a large storage dam can undergo drastic changes that impact the downstream environment when released (McCully, 2001). A storage dam that impounds a large reservoir of water for an extended time period will cause more extensive impacts to the physical and chemical characteristics of the water than a smaller dam with little storage capacity.

Several physical changes are possible when dams are introduced into a stream or river, including changes in:

- Instream water velocities
- Timing and duration of flows
- Flow rates
- Sediment transport capacities
- Turbidity
- Temperature
- Dissolved gasses

Similarly, changes are possible to water chemistry as a result of damming rivers and streams, including changes to:

- Nutrients
- Alkalinity and pH
- Metals and other toxic pollutants
- Organic matter

The nature and severity of impacts will depend on location in the river or stream, in relation to the upstream or downstream side of the dam, the storage time of the impounded water, and the operational practices at the dam. Many of the above impacts are also interrelated. For example, changes in temperature may result in changes in dissolved oxygen levels, nutrient dynamics, and the solubility of metals. The following sections discuss some of the possible physical and chemical changes to water quality in the impoundment/reservoir and downstream of a dam.

Water Quality in the Impoundment/Reservoir

As water approaches a dam from upstream, the stream velocity slows down considerably, creating a lake-like environment. The water builds up behind the dam and forms a basin (i.e., impoundment, reservoir) that is deeper than the previous stream flow. The height of the dam and its operational characteristics will determine how much water is stored and the length of storage. The extent of impacted stream area above the dam is influenced by the size of the dam installed, how much water is released, and how often water is released. For example, a small run-of-the river dam constructed to divert water for a millrace will have minimal storage capacity and may only store water for several hours or less. In this case, velocities may decrease, but the magnitude depends on the needs and operation of the diversion. The length of upstream channel that is impacted should be relatively small.

In contrast, a large flood control dam and reservoir may have many months of storage and severely alter instream velocities for long distances upstream. Topography surrounding the original stream channel and storage volume will be important parameters determining the length of stream channel affected by the large dam. The volume and frequency of discharges from the dam will also determine how much of the upstream channel is impacted with lower instream velocities as a result of the dam.

Dams act as a physical barrier to the movement of suspended sediments and nutrients downstream (McCully, 2001). When the stream flow behind a dam slows, the sediment carrying capacity of the water decreases and the suspended sediment settles onto the reservoir bottom. Any organic compounds, nutrients, and metals that are absorbed to the sediment also settle and can accumulate on the reservoir bottom.

Turbidity associated with sediment varies, depending on particle sizes of the sediment and the length of time water is held. Longer holding times in the reservoir could result in periodic episodes of high turbidity from upstream storm events that carry sediment rich stormwater, especially if the sediment is predominantly very fine clay particles. Turbidity may also increase as a result of planktonic algal growth in a reservoir.

The increased depth of the water in reservoirs reduces the volume of water exposed to solar radiation and ambient temperatures. Once the flow is controlled by the operation of the dam and the reservoir is mixed primarily by winds, temperature variations can become established within the reservoir. This can cause thermal stratification where, compared to the bottom, surface layers become warmer in the summer and cooler in the winter. In deeper reservoirs, the deepest layers may become nearly constant in temperature throughout the year. Changes in temperature can impact other water quality and biological processes in the reservoir, including nutrient cycling, oxygen content, metal speciation, and changes in predominant fish species. Since the density of water is a function of water temperature, thermal stratification creates density gradients within the impoundment. As density gradients become established, exchanges of gases and chemicals between gradients decrease. For example, in a stratified impoundment well aerated surface waters often do not mix with hypolimnetic water and result in poorly oxygenated strata below the surface waters.

Nutrients are affected by dams, which can trap the nutrients in the impoundment/reservoir. When nutrients accumulate, the reservoir might become nutrient enriched (i.e., eutrophic). In warmer seasons, concentrated nutrients in waters exposed to light can promote growth of algae and other aquatic plants, which consume nutrients and release oxygen (during photosynthesis) and carbon dioxide (during respiration). When algae and other aquatic plants complete their growth cycles, they die and sink to the bottom of an impoundment. Microbial decomposition of the highly organic dead plant materials may release nutrients back into the water column. Microbial decomposition of the dead plant and algal cells in aerobic conditions consumes oxygen, which can rapidly deplete bottom waters of dissolved oxygen. Under anaerobic conditions, microbial decomposition can produce potentially toxic concentrations of gases, such as hydrogen sulfide.

The operational characteristics of a dam will influence nutrient levels in water releases. For example, water released form the surface of an impoundment may contain seasonally varying forms and levels of nutrients. During periods of algal growth, releases may contain lower levels of dissolved nutrients and higher levels of organic materials (algae) containing nutrients. When algal growth is not occurring, releases may contain higher levels of dissolved nutrients.

Anaerobic (oxygen-depleted) environments, which are typical of deeper waters in reservoirs, can result in several changes to the water chemistry. For example, as by-products of organic matter decomposition in an anaerobic environment, ammonia and hydrogen sulfide concentrations can become elevated (Pozo et al., 1997 and Freeman, 1977). Highly acidic (or highly alkaline) waters tend to convert insoluble metal sulfides to soluble forms, which can increase the concentration of toxic metals in reservoir waters (FISRWG, 1998). Nutrients and metals will transform at different rates and in a specific order, called redox order.

Changes in one water quality parameter in a reservoir/impoundment can impact other water quality parameters, causing a cycling of events to occur. For example, increased sedimentation (from internal or external sources) can lead to more organic matter remaining in the reservoir, resulting in more biochemical oxygen demand, potentially lower dissolved oxygen, and other changes to water chemistry, such as pH and metal solubility. Periodic growth and then die-off of aquatic plants and algae creates additional variable cycling of organic matter in the reservoir. The following references may provide additional detail on the complex water quality changes that can occur in impoundments and reservoirs:

- Holdren, C., W. Jones, and J. Taggart. 2001. *Managing Lakes and Reservoirs*. North American Lake Management Society and Terrene Institute, in cooperation with the Office of Water, Assessment and Watershed Protection Division, U.S. Environmental Protection Agency, Madison, WI.
- Thornton, K.W., B.L. Kimmel, and F.E. Payne. 1990. *Reservoir Limnology: Ecological Perspectives*. John Wiley & Sons, Inc., New York.
- U.S. Army Corps of Engineers. No date. *The WES Handbook on Water Quality Enhancement Techniques for Reservoirs and Tailwaters*. U.S. Army Corps of Engineer Research and Development Center Waterways Experiment Station, Vicksburg, MS.

Water Quality Downstream of a Dam

The physical and chemical changes that occur to the water quality in an impoundment/reservoir have a large impact on the water released downstream of a dam. As previously stated, the presence of a dam can alter water velocities above and below the dam. In smaller dams with little storage capacity, velocities may slow locally and recover to an undisturbed state shortly downstream from the dam. When dams store large volumes of water in a reservoir, the operation of the dam will have a major impact on the downstream velocities and flows. Unless the dam is operated to consistently release water at flows near pre-dam levels, downstream areas will have flows and velocities that are directly related to the volume of water released in a given time period. The downstream flow characteristics will become a function of the operation of the dam, including the timing and duration of releases, the depth of reservoir intakes, and other physical characteristics of the release.

On the Columbia River, research found that prior to construction of dams, average water temperatures fluctuated more diurnally with cooler nighttime temperatures as compared with the existing average water temperatures. With the dams in place, cooler weather tends to cool the free flowing river but have little effect on the average temperature of the impounded river (USEPA, 2003c). To support a healthy aquatic ecosystem, water quality standards for temperature have been developed under the Clean Water Act. For example, a water temperature standard of 68 °F, maximum, was established for the mainstem Columbia and Lower Snake Rivers. Dam operators are required to maintain water in the Columbia River below the maximum. In addition, there are water quality standards for other critical water quality parameters, which are important to salmon recovery and promoting the general health of the Columbia and Snake River ecosystems (American Rivers, 2003).

When dams trap sediment upstream, water released from the dam may be starved of sediment and have an increase in erosive capacity. Along with trapping sediment, nutrients may also be trapped above the dam. When the nutrients are trapped and unavailable, sensitive downstream habitats and populations may be affected.

Whether the water is released from the surface or bottom of the reservoir can have a large impact on the characteristics of the water. The impacts of water outflows below a dam are an outcome of the seasonal temperature fluctuations and the outflow positioning. Seasonal temperature profiles in reservoirs are highly variable and dependent upon complex set of factors including tributary inflow, basin morphometry, drawdown and discharge characteristics, and the degree of stratification (Wetzel, 2001). Compared to natural temperatures, in summer, elevated temperatures in surface water releases can increase downstream river temperatures, whereas bottom water releases can be expected to decrease water temperatures. The opposite effect is generally observed in the winter due to changes in the water temperature gradient (USACE, 1999 in Oliver and Fidler, 2001).

Some impacts downstream can be perceived as beneficial to some and negative to others. For example, when water released from a dam is cooler than water downstream and it causes the downstream system to become colder, trout might relocate to this new habitat and displace native warm water species. Although increased trout is viewed by some as a positive effect, displacing native species may not be perceived as beneficial to others.

Suspended Sediment and Reduced Discharge

Whether the release water originates from the surface or the bottom of the reservoir, the suspended sediment has typically settled out of the water column and thus the water released from behind the dam is usually quite clear (Simons and Senturk, 1992). This clear water can easily pick up and carry a sediment load and have an increase in erosive capacity. Because of the rock lined channels of bank stabilization and navigation projects that usually occur below these reservoirs, the only place that the clear waters can find the sediments they need is in the streambed or navigation channel. This leads to channel deepening or bed degradation, which in turn lowers water tables and drains floodplain channels and backwaters (Rasmussen, 1999). Streambed and streambanks will continue to erode until an equilibrium suspended sediment load is established. Without sediment from upstream sources, downstream streambanks, streambeds, sandbars, and beaches can erode away more quickly (FISRWG, 1998). See Section 1 (Channelization and Channel Modification) for more detail on the relationship of sediment to stream channel morphology.

A reduction in the discharge and sediment load generally results in degradation of the channel close to the dam and sedimentation downstream due to the increased supply from the erosion near the dam. Degradation may eventually migrate downstream, but is typically most dramatic the first few years following construction of the dam (Biedenharn et al., 1997). In addition, the physical impact of the discharge will depend, in part, on the channel substrate. A fine silt and sand channel bottom may experience more extensive erosion than a bed rock or cobble substrate.

Lower flow conditions below a dam within a tidally influenced basin can lead to changes in water chemistry. The impact of lower freshwater flow into estuaries was extensively studied in San Francisco Bay. Nichols et al. (1986) provide a detailed history of changes to freshwater inflows to San Francisco Bay. They also provide a summary of the impacts, which include the ecological and water quality effects. A study comparing an unregulated river and a dam regulated river found a significant difference in the water quality chemistry that included an analysis of levels of sodium, potassium, calcium, phosphorus, electrical conductivity and pH in the middle and lower reaches of the rivers. These differences were attributed to increased tidal influence as a result of lower outflow volumes of fresh water from the dam (Colonnello, 2001). In addition, a decreased discharge from the dam and increased tidal influence can prolong the flushing time or the time it takes water to move through a system. This causes the nutrients and pollutants within the water to remain concentrated in areas below the dam near estuaries.

C. Biological and Habitat Impacts

The presence of a dam causes physical and chemical changes to the water quality. These, in turn, have an impact on the entire biological community including fish, algae, and streamside vegetation. Impacts to the biological community differ upstream and downstream of a dam and are discussed below. Dams disrupt spawning, increase mortalities from predation, change instream and riparian habitat, and alter plant and benthic communities. Resulting fish populations after dam construction may thrive and become well established, but are very different than populations prior to installing the dam. For example, upstream of the dam, a fish population may change from a cold-water salmonid fishery to one that is dominated to cool- or warm-water. A once thriving native trout population may become a largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*) dominated system. Similarly, downstream conditions may also change. In southern states, streams that once supported catfish and other tolerant warm-water species may now be able to support a trout fishery because of cold-water releases from bottom waters behind a dam. Dams prevent the movement of organisms throughout the river system (Morita and Yamamoto, 2002). Researchers found that fragmenting habitat by damming a river caused the disappearance of a fish species in several upstream locations and further disappearances were predicted (Morita and Yamamoto, 2002).

The effects of river damming were evaluated in a study comparing a regulated river to an unregulated river in the Green River Basin in Colorado. Prior to installation of the dam in Green River in 1962, Green River and the Yampa River were similar in riparian vegetation and fluvial processes. Comparison of the now regulated Green River and the free-flowing Yampa River found distinctive vegetation differences between the parks that surround the rivers. The channel form of Green River has undergone three stages of morphologic change that have transformed the historically deep river into a shallow braided channel. The Yampa River has remained relatively unchanged. The land surrounding the Green River now consists of marshes with anaerobic soil that supports wetland species and terraces with desert species adapted to xeric soil conditions. The meandering Yampa River has maintained its original surroundings. Its frequently flooded bars and high floodplains provide a wide range of habitats for succession of riparian vegetation (Merritt and Cooper, 2000).

Flood control and hydropower projects influence a river's hydrograph. Historically, normal river hydrographs featured a rise in water level elevation corresponding to spring rains, and a summer or fall rise corresponding to snowmelt in the mountains, or fall rainfall. Native species evolved under these scenarios and used such water level rises to trigger spawning movements onto floodplains and in the case of birds, for nesting on islands. Additionally, they were important in providing feeding and resting areas for spring and fall waterfowl migrations. Under management scenarios for commercial navigation, river water level elevations are raised in the spring and held stable throughout the navigation season, virtually eliminating the triggering mechanisms native species used to reproduce and complete their life cycles. Because of this, many native riverine species often fail to spawn or nest, and are becoming increasingly threatened (Rasmussen, 1999). Additionally, stabilization of periodic flooding has also lead to the loss of ephemeral wetlands and may lead to the accumulation of sediments in nearshore areas, thus negatively affecting fish spawning areas (NRC, 1992).

Dams can lead to increased predation of fish in several ways. A dam causes populations of fish to concentrate on both the upstream and downstream sides leading to the likelihood of increased predation. Changes in the habitat adjacent to a dam can make conditions more suitable to predation. Dams can cause the migration process to be delayed, which also leads to increased predation (Larinier, 2000).

The physical and chemical changes to water released from a dam, including reduced streamflow variability and decreased sediment loads, may impact the biological community. Increased water clarity and reduced streamflow variability just below a dam usually result in a greater abundance of periphyton or other plants as compared with other locations in the river (Stanford and Ward, 1996). This can then affect the benthic community and other organisms within the food web. A slowed stream flow velocity with decreased turbulence can also encourage the growth of phytoplankton blooms (Decamps, 1988). This is not the case with hydroelectric dams with large, sudden releases of water that can scour the bottom of the channel to the extent that there is a nearly complete removal of the plant communities (Allan, 1995).

Case Study: Fox River Fish Passage Feasibility Study

There are 15 mainstem dams and numerous tributary dams in the Illinois portion of the Fox River watershed. The 15 Fox River dams are impounding 47% of river miles and 55% of surface area in the nearly 100 miles of river between the Chain of Lakes and Dayton, Illinois. Many of these dams were originally built in the 1800s to provide mechanical power for grist or lumber mills, but today serve little function except to maintain flat-water pools and impoundments upstream of the dams. In the winter of 2002 the Max McGraw Wildlife Foundation completed a two-year study to determine the effects of dams on fisheries, macroinvertebrates, physical habitat, and water quality in a 100-mile stretch of the Fox River between the Chain of Lakes and Dayton, Illinois. Cooperators on this project include the USEPA, the Illinois Department of Natural Resources, and Steve Gephard, a Fish Passage Specialist from Connecticut.

Sampling for the study took place during summer low-flow conditions at 40 sites located in free-flowing river areas directly below dams, impounded river directly above dams, and free-flowing or impounded mid-segment areas between dams. Results convincingly showed that dams are reducing biodiversity of fishes and altering macroinvertebrate communities on the Fox River. Dams appeared to influence these aquatic organisms by degrading habitat and water quality conditions and fragmenting the river by acting as barriers to fish movement.

Based on the impacts found, the report suggests several options to alleviate the impacts. Options included complete dam removal and river restoration or retrofitting dams with ramps, fishways, or bypass channels to provide fish and/or canoe passage. The data suggest that dam removal is the best option when the ecological health of the river is of prime consideration. Removing dams can eliminate barriers to migration for all types and sizes of fish, restore high quality river habitat, and eliminate lake-like conditions that support high algal biomass and substandard DO levels. Ramps, fishways, and bypass channels will allow fish to get around or over dams but will do little or nothing to improve habitat and water quality conditions in the river. These alternatives should be considered only when dam removal is ruled out as an option. Determining the correct passage option for an individual dam is a complicated decision involving many stakeholders (i.e., dam owners, government agencies, local municipalities, organizations, and the public) and a variety of social, economic, and environmental issues. A project final report summarizes all of the study data and recommends that fish passage be considered at all Fox River dams.

Data regarding the impacts of dam modification and removal on the Fox River is being generated from the South Batavia Dam Project, which was initiated due to poor structural condition and safety hazards from the dam located on the Fox River. In 2001, a feasibility study was performed to determine the future of the South Batavia Dam. The study determined that future options include rebuilding the dam, modifying the dam spillways by lowering the dam or constructing a rock ramp that extends downstream from the face of the dam, or removing the dam altogether. Information collected during this project will provide useful data concerning stream community response and aid in the decision process for other dams within the Fox River basin. Information on the status of the project can be obtained at the South Batavia dam project website *http://www.southbataviadam.com*.

Sources:
Santucci, Victor J. Jr., Research Biologist, Max McGraw Wildlife Foundation, Dundee, Illinois. *Fox River News* Winter 2002. http://www.foxriverecosystem.org/dams.htm and http://www.mcgrawwildlife.org/main.taf?p=4,5,4. Accessed July 2003.

Robert H. Anderson & Associates, Inc. 2001. *South Batavia Dam Project*. http://www.southbataviadam.com. Accessed July 2003.

Case Study: Cuyahoga River in Ohio

The Ohio Environmental Protection Agency (OEPA) identified the Middle Cuyahoga (located between Lake Rockwell Dam north of Kent and the Ohio Edison Dam in Cuyahoga Falls) as a "priority impaired waterway." This designation was based on low DO, excessive nutrient levels, and habitat damage. Fish, aquatic insects, and macroinvertebrates are all adversely affected by poor water quality. Used as a source of drinking water and for recreational purposes, maintaining the water quality of the Middle Cuyahoga is of importance in several ways.

The Middle Cuyahoga is impaired primarily as a result of two large dam pools, where water slows or stands for about two days and loses dissolved oxygen. Kent Dam is 14 ft high with a dam pool about 1/3 mile long and Munroe Falls Dam is 11.5 ft high with a dam pool over 4 miles long. The dams are barriers to fish passage and aquatic habitat in the dam pools is unhealthy for many desirable species. The stagnant nature of the Munroe Falls dam pool has resulted in oxygen-depleted waters with excessive vegetation and algal growth. To meet clean water standards, OEPA recommended releasing 5 million gallons per day (mgd) from Lake Rockwell, with a guaranteed minimum of 3.5 mgd. OEPA also called for modifying the dams in Kent and Munroe Falls to provide swifter flows in the river.

The *Total Maximum Daily Loads (TMDL) for the Middle Cuyahoga River* report found the river to be in non-compliance. As a result, three actions that would result in the largest improvements to water quality were determined. They include 1) a minimum release from Lake Rockwell of at least 3.5 mgd of high quality water, 2) modification or removal of the Munroe Falls Dam to reduce or eliminate the dam pool, 3) and modification or removal of the Kent Dam to reduce or eliminate the dam pool. A copy of the final TMDL can be found at http://www.epa.state.oh.us/dsw/tmdl/midcuy.html.

In response to OEPA's *Total Maximum Daily Loads for the Middle Cuyahoga River* report and the issuance of a new discharge permit at Kent's treatment plant, the City of Kent initiated a study called the *Kent Dam Pool Water Quality Improvement Project* in March 2000. In January of 2001 as part of the study, a report was submitted to the City by an engineering consultant, recommending that a bypass of the river around the east side of the dam be installed. This alternative would include removal of the sediment accumulated behind the dam, which would expose the river's bedrock and produce an environment similar to the natural river downstream of the dam. This alternative was selected and is estimated to cost $1.8 million to $2.5 million. The project is slated for completion at the end of 2003 or beginning of 2004 and is contingent upon attaining several permits and finalizing an agreement between the City of Kent, OEPA, USEPA, the Ohio Historical Society, and the USACE.

At Munroe Falls, OEPA and Summit County's Department of Environmental Services chose an alternative that lowers the 11.5 ft dam by 6 ft to increase water velocity, which would maintain higher DO concentrations and decrease the aerial extent of the dam pool. The project also includes a fish passage around the southern end of the dam and a portage for boaters along the dam's north shore. The $1.4 million project is expected to start by mid-August 2003 and could take 12 to 18 months to complete. A $500,000 grant was obtained from OEPA. This money, in combination with $445,000 from the state loan program, will be used to restore and improve stream banks and wildlife habitats that will be exposed as a result of the project for three miles upstream of the dam.

Sources:

Brown, R. 2002. *Frequently Asked Questions About the Middle Cuyahoga River* http://www.kentenvironment.org/middle_cuyahoga.htm. Accessed June 2003. [Link not active]

Brown, R. No Date. *The Cuyahoga River.* http://www.kentenvironment.org/HISTORY%20OF%20THE%20RIVER%201.htm. Accessed June 2005.

Dimoff, K. Ohio Environmental Council. 2001. *The Cuyahoga: Looking at "total" pollution in U.S. rivers.* http://www.glu.org/english/information/newsletters/15_3-fall-2001/Cuyahoga-USrivers.html. Accessed July 2005

Downing, B. 2003. Dam changes tap river's possibilities. *The Beacon Journal.* http://www.ohio.com/mld/ohio/5950460.htm. Accessed August 2003. [Link not active]

Summit County, Ohio. 2003. *Munroe Falls Dam Modification Project.* http://www.co.summit.oh.us/executive/mfd/mfdproblem.htm. Accessed July 2003.

Management Measure for Erosion and Sediment Control for the Construction of New Dams and Maintenance of Existing Dams

Management Measure
1) Reduce erosion and, to the extent practicable, retain sediment onsite during and after construction. 2) Prior to land disturbance, prepare and implement an approved erosion and sediment control plan or similar administrative document that contains erosion and sediment control provisions.

A. Introduction

The purpose of this management measure is to prevent sediment from entering surface waters during the construction or maintenance of dams. This management measure emphasizes the importance of minimizing sediment loss to surface waters during both dam construction and maintenance. It is essential that proper erosion and sediment control practices be used to protect surface water quality because of the high potential for sediment loss directly to surface waters. Eroded sediment from construction sites creates many problems including adverse impacts to water quality, critical instream and riparian habitats, submerged aquatic vegetation (SAV) beds, recreational activities, and navigation (Schueler, 1997). Sediment and erosion control practices can be borrowed from other applications, such as urban development and construction activities. This management measure focuses on dam related erosion and sediment control.

Two broad performance goals constitute this management measure: minimizing erosion and maximizing the retention of sediment onsite. These performance goals allow for flexibility in specifying practices appropriate for local conditions.

At the state and local levels, this measure can be incorporated into existing erosion and sediment control (ESC) programs or, if such programs are lacking, state or local governments could develop them. Erosion and sediment control is intended to be part of a comprehensive land use or watershed management program.

ESC plans are important for controlling the adverse impacts of dam construction. ESC plans ensure that provisions for control measures are incorporated into the site planning stage of development. ESC plans also provide for prevention of erosion and sediment problems and accountability if a problem occurs (MDEP, 1990). In many municipalities, erosion and sediment control plans are required under ordinances enacted to protect water resources (Table 2.2). These plans describe the activities construction and maintenance personnel will use to reduce soil erosion and contain and treat runoff that is carrying eroded sediments. ESC plans typically include descriptions and locations of soil stabilization practices, perimeter controls, and runoff treatment facilities that will be installed and maintained before and during construction activities. In addition to special area considerations, the full ESC plan review inventory should include:

- Topographic and vicinity maps
- Site development plan
- Construction schedule
- Erosion and sedimentation control plan drawings
- Detailed drawings and specifications for practices
- Design calculations
- Vegetation plan

Table 2.2 Examples of ESC Plan Requirements for Selected States

Location	General Requirements for ECS Plan
Delaware	ESC plans required for sites over 5,000 ft^2. Temporary or permanent stabilization must occur within 14 days of disturbance.
Florida	ESC plans required on all sites that need a runoff management permit.
Georgia	ESC plan required for all land-disturbing activities.
Indiana	ESC plan required for sites over 5 acres.
Maine	ESC plans required for sites adjacent to a wetland or waterbody. Stabilization must occur at completion or if no construction activity is to occur for 7 days. If temporary stabilization is used, permanent stabilization must be implemented within 30 days.
Maryland	ESC plans required for sites over 5,000 ft^2 or 100 yd^3.
Michigan	ESC plans required for sites over 1 acre or within 500 ft of a waterbody. Permanent stabilization must occur within 15 days of final grading. Temporary stabilization is required within 30 days if construction ceases.
Minnesota	ESC plans required for land development over 1 acre.
New Jersey	ESC plans required for sites over 5,000 ft^2.
North Carolina	ESC plans required for sites over 1 acre. Controls must retain sediment on-site. Stabilization must occur within 30 days of completion of any phase of development.
Ohio	ESC plans required for sites over 5 acres. Permanent stabilization must occur within 7 days of final grading or when there is no construction activity for 45 days.
Oklahoma	ESC plans required for sites over 5 acres.
Pennsylvania	ESC plans required for all sites, but the state reviews only plans for sites over 25 acres. Permanent stabilization must occur as soon as possible after final grading. Temporary stabilization is required within 70 days if construction ceases for more than 30 days. Permanent stabilization is required if the site will be inactive for more than 1 year.
South Carolina	ESC plans required for all sites unless specifically exempted. Perimeter controls must be installed. Temporary or permanent stabilization is required for topsoil stockpiles and all other areas within 7 days of disturbance.
Virginia	For areas within the jurisdiction of the Chesapeake Bay Preservation Act, no more land is to be disturbed than necessary for the project. Indigenous vegetation must be preserved to the greatest extent possible.
Washington	ESC provisions are incorporated into the state runoff management plan.
Wisconsin	ESC plans required for all sites over 4,000 ft^3. Temporary or permanent stabilization is required within 7 days.

(Adapted from USEPA, 1993; Environmental Law Institute, 1998)

Some erosion and soil loss is unavoidable during land-disturbing activities. Although proper siting and design help prevent areas prone to erosion from being developed, construction activities invariably produce conditions where erosion can occur. To reduce the adverse impacts associated with construction activities at dams, the construction management measure suggests a system of nonstructural and structural erosion and sediment controls for incorporation into an ESC plan.

Nonstructural controls address erosion control by decreasing erosion potential, whereas structural controls are both preventive and mitigative because they control erosion and sediment movement. Brown and Caraco (1997) identified several general objectives that should be addressed in an effective ESC plan:

- *Minimize clearing and grading* – clearing and grading should occur only where absolutely necessary to build and provide access to structures and infrastructure. This approach reduces earth-working and ESC control costs by as much as $5,000 per acre (Schueler, 1995). Clearing should be done immediately before construction, rather than leaving soils exposed for months or years (SQI, 2000).

- *Protect waterways and stabilize drainage ways* – all natural waterways within a development site should be clearly identified before construction activities begin. Clearing should generally be prohibited in or adjacent to waterways. Sediment control practices such as check dams might be needed to stabilize drainage ways and retain sediment on-site.

- *Phase construction to limit soil exposure* – construction phasing is a process where only a portion of the site is disturbed at any one time to complete the required building in that phase. Other portions of the site are not cleared and graded until exposed soils from the earlier phase have been stabilized and the construction nearly completed.

- *Stabilize exposed soils immediately* – seeding or other stabilization practices should occur as soon as possible after grading. In colder climates, a mulch cover is needed to stabilize the soil during the winter months when grass does not grow or grows poorly.

- *Protect steep slopes and cuts* – wherever possible, clearing and grading of existing steep slopes should be completely avoided. If clearing cannot be avoided, practices should be implemented to prevent runoff from flowing down slopes.

- *Install perimeter controls to filter sediments* – perimeter controls are used to retain sediment-laden runoff or filter it before it exits the site. The two most common perimeter control options are silt fences and earthen dikes or diversions.

- *Employ advanced sediment-settling controls* – traditional sediment basins are limited in their ability to trap sediments because fine-grained particles tend to remain suspended and the design of the basin themselves is often simplistic. Sediment basins can be designed to improve trapping efficiency through the use of perforated risers; better internal geometry; the installation of baffles, skimmers, and other outlet devices; gentler side slopes; and multiple-cell construction.

ESC plans ensure that provisions for control measures are incorporated into the site planning stage of development help to reduce the incidence of erosion and sediment problems, and improve accountability if a problem occurs. An effective plan for runoff management on construction sites controls erosion, retains sediments on-site to the extent practicable, and reduces the adverse effects of runoff. Climate, topography, soils, drainage patterns, and vegetation affect how erosion and sediment should be controlled on a site (Washington State Department of Ecology, 1989).

ESC plans should be flexible to account for unexpected events that occur after the plans have been approved, including:

- Discrepancies between planned and as-built grades
- Weather conditions
- Altered drainage
- Unforeseen construction requirements

Changes to an ESC plan should be made based on regular inspections that identify whether the ESC practices were appropriate or properly installed or maintained. Inspecting an ESC practice after storm events shows whether the practice was installed or maintained properly. Such inspections also show whether a practice requires cleanout, repair, reinforcement, or replacement with a more appropriate practice. Inspecting after storms is the best way to ensure that ESC practices remain in place and effective at all times during construction activities.

Because funding for ESC programs is not always dedicated, budgetary and staffing constraints may thwart effective program implementation. Brown and Caraco (1997) recommend several management techniques to ensure that ESC programs are properly administered:

- Local leadership committed to the ESC program
- Redeployment of existing staff from the office to the field or training room
- Cross-training of local review and inspection staff
- Submission of erosion prevention elements for early planning reviews.
- Prioritization of inspections based on erosion risk
- Requirement of designers to certify the initial installation of ESC practices
- Investment in contractor certification and private inspector programs
- Use of public-sector construction projects to demonstrate effective ESC controls
- Enlistment of the talents of developers and engineering consultants in the ESC program
- Revision and update of the local ESC manual

An allowance item that acts as an additional “insurance policy” for complying with the erosion and sediment control plan can be added to bid or contract documents (Deering, 2000a). This allowance covers costs to repair storm damage to erosion and sediment control measures as specified in the erosion and sediment control plan. This allowance does not cover storm damage to property that is not related to the erosion and sediment control plan, because this would be covered under traditional liability insurance. Damage caused by severe and continuous rain events, windblown objects, fallen trees or limbs, or high-velocity, short-term rain events on steep slopes and existing grades would be covered by the allowance, as would deterioration from exposure to the elements or excessive maintenance for silt removal. The contractor is responsible for being in compliance with the erosion and sediment control plan by properly implementing and maintaining all specified measures and structures. The allowance does not cover damage to practices caused by improper installation or maintenance.

Case Study: Effects of Erosion and Sediment Control Practices on Stream Biological Conditions

A study conducted by University of North Carolina researchers from 1996 to 1999 measured the effects of erosion and sediment control regulations, inspections, and enforcement on stream biological condition at 17 construction sites in central North Carolina. At each site, upstream, downstream, and at-site samples were taken before construction began, during the peak land disturbance, and after the project was completed and released by the regulatory agency. Benthic and fish communities were sampled in addition to several water chemistry variables and leaf litter decomposition rates. The researchers found the following results:

- Virtually all at-site samples showed some degradation relative to upstream controls
- Impacts at sites downstream from construction sites were highly variable
- Degree of degradation was significantly affected by enforcement activities: stronger enforcement resulted in less environmental impact on the streams
- The stringency of the erosion and sediment control regulations proved unimportant compared to enforcement

The researchers concluded that staffing, workload, attitudes, and enforcement activities strongly influenced downstream conditions.

Source:
Reice, S.R., and R.N. Andrews. 2000. *Effectiveness of Regulatory Incentives for Sediment Pollution Prevention: Evaluation Through Policy Analysis and Biomonitoring*. Prepared for the U.S. Environmental Protection Agency by the University of North Carolina, Chapel Hill, under EPA Grant No. R 825286-01-0.

Maintenance activities at dams can also impact surface waters. It is important to establish a program of regular safety inspection of the dam's infrastructure and dam maintenance. Safety inspection of a dam is a program of regular visual inspection using simple equipment and techniques. It is the most economical means of ensuring the long-term safety and survival of a dam structure. By regularly monitoring the condition and performance of the dam and its surroundings, adequate warning of potentially unsafe trends will enable timely maintenance. Being able to recognize the signs of potential problems and failure, as well as what to do and who to contact, is vital. Partial or total failure of a dam may cause extensive damage to downstream areas, including wetlands, riparian areas, stream channels, and other ecologically important lands, for which the owner is likely to be held liable. Common law liability may also apply if proof of negligence is established. Then there is the expensive repair costs and lost income. Regularly monitoring of a dam and its surroundings will enable timely maintenance of potentially unsafe trends and protect against possible water quality impairments.

The main areas of dam structural failure are:

- Dispersive clays used in berms and other earthen structures
- Seepage and leakage at the base or along pipes
- Erosion, including wave action, stock damage and spillways
- Cracking and movement of structural components
- Defects in associated structures

- Vegetation, including catchment protection and weed control

Operation and maintenance is not only applied to large dams. Many owners of small dams, like those on farm ponds, should regularly inspect their dams for maintenance needs. For example, Figure 2.1 illustrates some of the common maintenance issues of smaller dams. NRCS can provide technical assistance to small dam owners for operation and maintenance activities. Contact your local USDA Service Center (http://offices.sc.egov.usda.gov/locator/app) to access NRCS in your community.

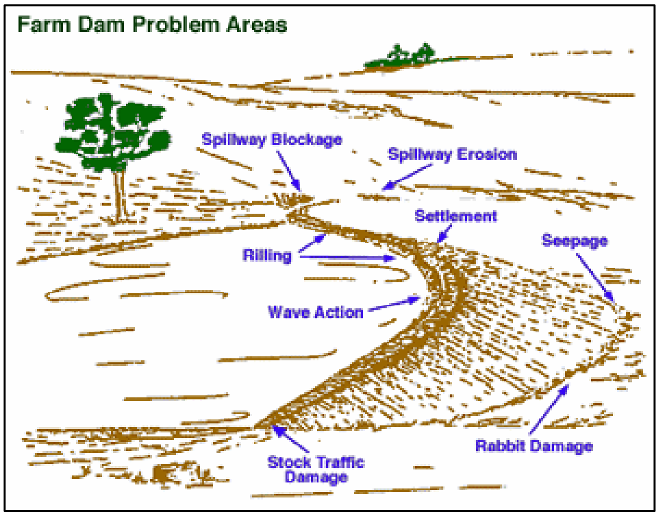


Figure 2.1 Operation and Maintenance of Smaller Dams (e.g., Dams on Private Farms) Source: Lewis, 1992.

Regular operation and maintenance efforts can lead to some dams being in need of repairs and/or upgrades. Designs for repairs and upgrades can involve replacing reinforced concrete riser (Figure 2.2) and impact basins (Figure 2.3), replacing rusted out corrugated metal pipe principal spillways, raising the top of the dams, widening the auxiliary spillways, and removing sediment from the flood pools (Figure 2.4). Project costs reported in Ohio have ranged from $175,000 on a small dam to $775,000 on the largest dam (Brate, 2004).

Figure 2.2 Construction on concrete riser (Brate, 2004)

Figure 2.3 Construction on the concrete riser (Brate, 2004)

Figure 2.4 Removing sediment from the flood pool (Brate, 2004)

B. Management Practices

The management measure generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices described below can be applied successfully to implement the management measure described for erosion and sediment control for the construction of new dams and maintenance of existing dams.

Erosion Control

Successful control of erosion and sedimentation from construction and maintenance activities can involve a system of management practices that targets each stage of the erosion process. The most efficient approach involves minimizing the potential sources of sediment from the onset. This means limiting the extent and duration of land disturbance to the minimum needed, and protecting surfaces once they are exposed. The second stage of the management practice system involves controlling the amount of runoff and its ability to carry sediment by diverting incoming flows and impeding internally generated flows. The third stage involves retaining sediment that is picked up on the project site through the use of sediment-capturing devices. On most sites successful erosion and sedimentation control requires a combination of structural and vegetative practices. All of these stages are better performed using advanced planning and good scheduling.

The timing of land disturbing activities and installation of erosion control measures must be coordinated to minimize water quality impacts. For large scale activities, the management practice system is typically installed in reverse order, starting with sediment capturing devices, followed by key runoff control measures and runoff conveyances, and then land clearing activities. Often, construction or maintenance activities that generate significant off-site sediment have failed to sequence activities in the proper order.

Erosion controls are used to reduce the amount of sediment that is lost during dam construction and to prevent sediment from entering surface waters. Erosion control is based on two main concepts: (1) minimizing the area and time of land disturbance and (2) quickly stabilizing disturbed soils to prevent erosion.

The effectiveness of erosion control practices can vary based on land slope, the size of the disturbed area, rainfall frequency and intensity, wind conditions, soil type, use of heavy machinery, length of time soils are exposed and unprotected, and other factors. In general, a system of erosion and sediment control practices can more effectively reduce offsite sediment transport than a single practice. Numerous nonstructural measures such as protecting natural or newly planted vegetation, minimizing the disturbance of vegetation on steep slopes and other highly erodible areas, maximizing the distance eroded material must travel before reaching the drainage system, and locating roads away from sensitive areas may be used to reduce erosion.

Table 2.3 shows examples of cost and effectiveness information for several erosion control practices.

Table 2.3 Cost and Effectiveness for Selected Erosion and Runoff Control Practices

Practice	Percent TSS removal	Effectiveness References	Cost (2001 dollars[a])	Cost References
Practices				
Chemical stabilization	Polyacrylamide: 77–93%	Roa-Espinosa et al., n.d.a	PAM: $1.30–$38.50/lb	Entry and Sojka, 1999; Sojka and Lentz, 1996
Erosion control blankets	70% wheat straw/30% coconut fiber: 98.7% Straw: 89.2%–98.6% Curled wood fiber: 28.8%–93.6% Jute mats: 60.6% Synthetic fiber: 71.2% Nylon monofilament: 53.0%	CWP, 1997a	Biodegradable materials: $0.50–$0.57/yd^2 Permanent materials: $3.00–$4.50/yd^2 Staples: $0.04–$0.05/staple	Erosion Control Systems, Inc., personal communication, March 14, 2001
Mulching	Reduction of soil loss: 53%–99.8% Reduction in water velocity: 24%–78%	Harding, 1990	Average: $0.38/yd^2 Range: $0.21–$0.87/yd^2	USEPA, 1993
Seeding	Average: 90% Range: 50%–100%	USEPA, 1993	Average: $0.10/yd^2 Range: $0.05–$0.25/yd^2 Maintenance costs: 15%–25% of installation costs	USEPA, 1993
Sodding	Range: 98–99%	USEPA, 1993	Average: $2.20/yd^2 Range: $1.10–$12/yd^2 Maintenance costs: 5% of installation costs	USEPA, 1993
Terraces	1%–12% slope: 70% less erosion 12%–18% slope: 60% less erosion 18%–24% slope: 55% less erosion	USEPA, 1993	Average: $6/linear ft Range: $1.20–$14.50/linear ft	USEPA, 1993
Prevention[b]				
Check dams			$100/dam (constructed of rock)	NAHB, 1995
Earth dike			Small dike: $2.50–$6.50/linear ft Large dikes: $2.50/yd^3	NAHB, 1995; SWRPC, 1991
Pipe slope drain			$5/linear ft for flexible PVC pipe; inlet and outlet structures additional	NAHB, 1995

[a] Cost adjusted for inflation using the Consumer Pricing Index (BLS, 2001)
[b] Practices do not have TSS removal because they convey water and prevent erosion.
[Note: Costs will be updated when the document is finalized]

The following practices have proven to be useful in controlling erosion and can be incorporated into ESC plans and used during dam construction as appropriate. These practices can be used during and after construction and throughout ongoing maintenance activities.

Provide Training

Provide education and training opportunities for designers, developers, and contractors. One of the most important factors determining whether erosion and sediment controls will be properly installed and maintained on a construction site is the knowledge and experience of the contractor and onsite personnel. Many communities require certification for key on-site employees who are responsible for implementing the ESC plan. Certification can be accomplished through municipally sponsored training courses; more informally, municipalities can hold mandatory preconstruction or prewintering meetings and conduct regular and final inspection visits to transfer information to contractors (Brown and Caraco, 1997). Information that can be covered in training courses and meetings includes the importance of ESC for water quality protection; developing and implementing ESC plans; the importance of proper installation, regular inspection, and diligent maintenance of ESC practices; and record keeping for inspections and maintenance activities.

Contractor/Developer Certification Programs in Delaware and Maine

Delaware requires contractor certification of responsible personnel for any foreman or superintendent who is in charge of on-site clearing and land-disturbing activities for sediment and runoff control associated with a construction project. Responsible personnel are required to complete a Department of Natural Resources and Environmental Control-sponsored or approved training program. All applicants seeking approval of a sediment and runoff plan must certify that all personnel involved in the construction project will have a certificate of attendance at a Department-sponsored or approve training course before initiation of any land-disturbing activity.

The Maine Department of Environmental Protection offers the Voluntary Contractor Certification Program (VCCP), which is a nonregulatory, incentive-driven program to broaden the use of effective erosion control techniques. The VCCP is open to any contractor who is involved with soil disturbance activities, including filling, excavating, landscaping, and other types of earthworks. For initial certification, the program requires attendance at two 6-hour training courses and the successful completion of a construction site evaluation. To maintain certification, a minimum of one 4-hour continuing education course within every 2-year period thereafter is required. Local soil and water conservation district personnel will complete construction site evaluations during the construction season. Certifications are valid until December 31 of the second year after issuance. Certification will entitle the holder to advertise services as a "DEP Certified Contractor" and to forgo the 14-day waiting period, which allows the Department time to approve or deny a notification, for Soil Disturbance and Stream Crossing Projects under the Department's Permit-by-Rule program.

Sources:

Delaware Department of Natural Resources and Environmental Control. 2000. *Sediment and Stormwater Regulations, Section 13*. http://www.dnrec.state.de.us/DNREC2000/Divisions/Soil/Stormwater/Regs/SSRegs_4-05.pdf. Accessed July 2005.

Maine Department of Environmental Protection. 1999. *Issue Profile: Voluntary Contractor Certification Program*. http://www.state.me.us/dep/blwq/training/ip-vccp.htm. Accessed March 2004.

Schedule Projects so Clearing and Grading are Done During Times of Minimum Erosion Potential

Often a project can be scheduled during the time of year that the erosion potential of the site is relatively low. In many parts of the country, there is a certain period of the year when erosion potential is relatively low and construction scheduling could be very effective. For example, in the Pacific region if construction can be completed during the 6-month dry season (May 1 to October 31), temporary erosion and sediment controls might not be needed. In some parts of the country erosion potential is very high during certain parts of the year such as the spring thaw in northern and high-elevation areas. During that time of year, snowmelt generates a constant runoff that can erode soil. In addition, construction vehicles can easily turn the soft, wet ground into mud, which is more easily washed off-site. Therefore, in the north, limitations could be placed on clearing and grading during the spring thaw (Goldman et al., 1986).

Phase Construction

Construction site phasing involves disturbing only small portions of a site at a time to prevent erosion from dormant parts (CWP, 1997c). Grading activities and construction are completed and soils are effectively stabilized on one part of the site before grading and construction commence at another. This is different from the more traditional practice of construction site sequencing, in which construction occurs at only one part of the site at a time but site grading and other site-disturbing activities typically occur all at once, leaving portions of the disturbed site vulnerable to erosion. To be effective, construction site phasing must be incorporated into the overall site plan early. Elements to consider when phasing construction activities include (CWP, 1997c):

- Managing runoff separately in each phase
- Determining whether water and sewer connections and extensions can be accommodated
- Determining the fate of already completed downhill phases
- Providing separate construction and residential accesses to prevent conflicts between residents living in completed stages of the site and construction equipment working on later stages

A comparison of sediment loss from a typical development and from a comparable phased project showed a 42 percent reduction in sediment export in the phased project (CWP, 1997c). Phasing can also provide protection from complete enforcement and shutdown of the entire project. If a contractor is in noncompliance in one phase or zone of a site, that will be the only zone affected by enforcement. This approach can help to minimize liability exposure and protect the contractor financially (Deering, 2000b).

Practice Site Fingerprinting

Often areas of a construction site are unnecessarily cleared. Site fingerprinting involves clearing only those areas essential for completing construction activities, leaving other areas undisturbed. Additionally, the proposed limits of land disturbance can be physically marked off to ensure that only the land area required for buildings, roads, and other infrastructure is cleared. Existing vegetation, especially vegetation on steep slopes, can be avoided.

Locate Potential Pollutant Sources Away from Steep Slopes, Waterbodies, and Critical Areas

Material stockpiles, borrow areas, access roads, and other land-disturbing activities can often be located away from critical areas such as steep slopes, highly erodible soils, and areas that drain directly into sensitive waterbodies.

Route Construction Traffic to Avoid Existing or Newly Planted Vegetation

Where possible, construction traffic should be directed over areas that must be disturbed for other construction activity. This practice reduces the net total area that is cleared and susceptible to erosion.

Protect Natural Vegetation with Fencing, Tree Armoring, and Retaining Walls or Tree Wells

Tree armoring protects tree trunks from being damaged by construction equipment. Fencing can also protect tree trunks, but it should be placed at the tree's drip line so that construction equipment is kept away from the tree. A tree's drip line is the minimum area around the tree in which the tree's root system should not be disturbed by cut, fill, or soil compaction caused by heavy equipment. When cutting or filling must be done near a tree, a retaining wall or tree well can be used to minimize the cutting of the tree's roots or the quantity of fill placed over the tree’s roots.

Stockpile Topsoil and Reapply to Revegetate Site

Because of the high organic content of topsoil, it is not recommended for use as fill material or under pavement. After a site is cleared, the topsoil is typically removed. Since topsoil is essential to establish new vegetation, it should be stockpiled and then reapplied to the site for revegetation, if appropriate. Although topsoil salvaged from the existing site can often be used, it must meet certain standards, and topsoil might need to be imported onto the site if the existing topsoil is not adequate for establishing new vegetation.

Cover or Stabilize Soil Stockpiles

Unprotected stockpiles are very prone to erosion, and therefore stockpiles must be protected. Small stockpiles can be covered with a tarp to prevent erosion. Large stockpiles can be stabilized by erosion blankets, seeding, and/or mulching.

Use Wind Erosion Controls

Wind erosion controls limit the movement of dust from disturbed soil surfaces and include many different practices. Wind barriers block air currents and are effective in controlling soil blowing. Many different materials can be used as wind barriers, including solid board fences, snow fences, and bales of hay. Sprinkling moistens the soil surface with water and must be repeated as needed to be effective for preventing wind erosion (Delaware DNREC, 2003); however, applications must be monitored to prevent excessive runoff and erosion.

Revegetate

Revegetation of construction sites during and after construction is the most effective way to permanently control erosion (Hynson et al., 1985). To select the right plants for your bioengineering project, note what native plant communities grow in the area. Avoid planting noxious or invasive grasses such as reed canary grass or ryegrass. Remove invasive plants such as yellow starthistle, English ivy, deadly nightshade, field morning glory, scotch broom, cheatgrass, and purple loosestrife. Use more of the same native plants in the bioengineering design, as these plants are most likely adapted to conditions to the area. Plants like willow, red osier dogwood, alder, ash, and cottonwood are well suited for bioengineering. They establish easily, grow quickly, and have thick root systems. Willow and dogwood cuttings are available for purchase from native plant nurseries or cuttings may be collected next to the project site, if the area is well vegetated (Oregon Association of Conservation Districts, 2004).

Mulching

Newly established vegetation does not have as extensive a root system as existing vegetation and therefore is more prone to erosion, especially on steep slopes. Additional stabilization should be considered during the early stages of seeding. This extra stabilization can be accomplished using mulches or mulch mats, which can protect the disturbed area while vegetation becomes established.

Mulching involves applying plant residues or other suitable materials on disturbed soil surfaces. Mulches and mulch mats include tacked straw, wood chips, and jute netting and are often covered by blankets or netting. Mulching alone should be used only for temporary protection of the soil surface or when permanent seeding is not feasible. The useful life of mulch varies with the material used and the amount of precipitation, but, generally, is approximately 2 to 6 months. Mulching and/or sodding may be necessary as slopes become moderate to steep, as soils become more erosive, and as areas become more sensitive. During the times of the year when vegetation cannot be established, mulch can be applied to moderate slopes and soils that are not highly erodible. On steep slopes or highly erodible soils, multiple mulching treatments may be required.

Sodding

Sodding permanently stabilizes an area with a thick vegetative cover. Sodding provides immediate stabilization of an area and can be used in critical areas or where establishing permanent vegetation by seeding and mulching would be difficult. Sodding is also a preferred option when there is high erosion potential during the period of vegetative establishment from seeding. According to the Soil Quality Institute (SQI, 2000), soils that have been compacted by grading should be broken up or tilled before placing sod.

Seeding

Seeding establishes a vegetative cover on disturbed areas and is very effective in controlling soil erosion once a dense vegetative cover has been established. Seeding establishes permanent erosion control in a relatively short amount of time and has been shown to decrease solids load by 99 percent (CWP, 1997a). The three most common seeding methods are (1) broadcast seeding, in which seeds are scattered on the soil surface; (2) hydroseeding, in which seeds are sprayed on the surface of the soil with a slurry of water (see Figure 2.5); and (3) drill seeding, in

Figure 2.5 Hydroseeding (Conwed Fibers, n.d.)

which a tractordrawn implement injects seeds into the soil surface. Broadcast seeding is most appropriate for small areas and for augmenting sparse and patchy grass covers. Hydroseeding is often used for large areas (in excess of 5,000 square feet) and is typically combined with tackifiers, fertilizers, and fiber mulch. Drill seeding is expensive and is cost-effective only on sites greater than 2 acres. For best results, bare soils should be seeded or otherwise stabilized within 15 calendar days after final grading. Denuded areas that are inactive and will be exposed to rain for 15 days or more can also be temporarily stabilized, usually by planting seeds and establishing vegetation during favorable seasons in areas where vegetation can be established. In very flat, nonsensitive areas with favorable soils, stabilization may involve simply seeding and fertilizing. The Soil Quality Institute (SQI, 2000) recommends that soils that have been compacted by grading should be broken up or tilled before vegetating.

To establish a vegetative cover, it is important to use seeds from adapted plant species and varieties that have a high germination capacity. Supplying essential plant nutrients, testing the soil for toxic materials, and applying an adequate amount of lime and fertilizer can overcome many unfavorable soil conditions and establish adequate vegetative cover. Specific information about seeds, various species, establishment techniques, and maintenance can be obtained from *Erosion Control & Conservation Plantings on Noncropland* (Landschoot, 1997) or a local Cooperative State Research, Education, and Extension Service (http://www.reeusda.gov) or Natural Resources Conservation Service (http://www.nrcs.usda.gov) office.

Surface Roughening

Roughening is the scarifying of a bare sloped soil surface with horizontal grooves or benches running across the slope. Roughening aids the establishment of vegetative cover, improves water infiltration, and decreases runoff velocity.

Soil Bioengineering

Soil bioengineering is the combination of biological, mechanical, and ecological concepts to control erosion and stabilize soil through the sole use of vegetation or a combination of vegetation and construction materials. These techniques can be used to address the erosion resulting from dam operation. Grading or terracing a problem streambank or eroding area and using interwoven vegetation mats, installed alone or in combination with structural measures, will facilitate infiltration stability. See Section 3 of this guidance document for additional streambank and shoreline protection techniques.

Riprap

A layer of stone designed to protect and stabilize areas subject to erosion, slopes subject to seepage, or areas with poor soil structure. Riprap can be used where vegetation cannot be established or in combination with bioengineering approaches. One bioengineering technique is using rock riprap at the toe and live stakes on the slope.

Install Erosion Control Blankets

Figure 2.6 Erosion control blanket (Conwed Fibers, n.d.)

Turf reinforcement mats (TRMs) combine vegetative growth and synthetic materials to form a high-strength mat that helps prevent soil erosion in drainage areas and on steep slopes (Figure 2.6) (USEPA, 1999). TRMs enhance the natural ability of vegetation to permanently protect soil from erosion. They are composed of interwoven layers of nondegradable geosynthetic materials such as polypropylene, nylon, and polyvinyl chloride netting, stitched together to form a three-dimensional matrix. They are thick and porous enough to allow for soil filling and retention. In addition to providing scour protection, the mesh netting of TRMs is designed to enhance vegetative root and stem development. By protecting the soil from scouring forces and enhancing vegetative growth, TRMs can raise the threshold of natural vegetation to withstand higher hydraulic forces on stabilization slopes, streambanks, and channels. In addition to reducing flow velocities, the use of natural vegetation provides removal of particulates through sedimentation and soil infiltration and improves the aesthetics of a site. In general, TRMs should not be used in the following situations:

- To prevent deep-seated slope failure due to causes other than surficial erosion
- When anticipated hydraulic conditions are beyond the limits of TRMs (see below) and natural vegetation
- Directly beneath drop outlets to dissipate impact force (although they can be used beyond the impact zone)
- Where wave height might exceed 1 foot (although they may be used to protect areas upslope of the wave impact zone)

The performance of a TRM-lined conveyance system depends on the duration of the runoff event to which it is subjected. For short-term events, TRMs are typically effective at flow velocities of up to 15 feet per second and shear stresses of up to 8 lb/ft^2. However, specific high-performance TRMs may be effective under more severe hydraulic conditions. Practitioners should check with manufacturers for the specifications and performance limits of different products. In general, the installed cost of TRMs ranges from \$5.25/yd^2 to \$15.75/yd^2 (USEPA, 1999; adjusted to 2001 dollars using BLS, 2001). Factors influencing the cost of TRMs include:

- The type of TRM material required
- Site conditions, such as the underlying soils, the steepness of the slope, and other grading requirements
- Installation-specific factors such as local construction costs

In most cases, TRMs cost considerably less than concrete and riprap solutions. For example, a project in Aspen, Colorado, used more than 23,000 yd^2 of TRMs to line channels for a horse ranch development project (Theisen, 1996). The TRMs were installed at a cost of \$9.20/yd^2

(adjusted to 2001 dollars using BLS, 2001). This cost was substantially less than the $20/yd^2 estimate for the rock riprap alternative.

Use Chemical Stabilization (PAM or Chemical Coagulation)

Polyacrylamide (PAM) is a polymer produced mainly for agricultural use to control erosion and promote infiltration on irrigated lands (Sojka and Lentz, 1996). Documentation of its effectiveness can be found in EPA's *National Management Measures to Control Nonpoint Source Pollution from Agriculture* (EPA 841-B-03-004). PAM is now being used for other land uses such as construction sites or urban areas to reduce erosion from disturbed areas (Aicardo, 1996; Roa-Espinosa et al., n.d.a). When applied to soils, PAM binds to soil particles and forms a gel that decreases soil bulk density, absorbs water, and binds fine-grained soil particles. PAM is not only used for erosion control but is also employed in municipal water treatment, paper manufacturing, food and animal feed processing, cosmetics, friction reduction, mineral and coal processing, and textile production.

PAM is available in powder form or as aqueous concentrate, blocks and cubes, or emulsified concentrate; each type has benefits and drawbacks that alter its applicability in different settings and by different application methods. PAM costs $1.30 to $38.50 per pound (Entry and Sojka, 1999; Sojka and Lentz, 1996; updated to 2001 dollars with BLS, 2001) and has been shown to achieve a 77 to 93 percent reduction in sediment loss from disturbed sites (Roa-Espinosa et al., n.d.a).

Application of PAM improves surface water quality by decreasing suspended solids and the phosphorus, nitrogen, pesticides, pathogens, salts, metals, and BOD usually associated with sediment loading. However, PAM may detrimentally affect ground water quality by increased leaching of nutrients, pesticides, and pathogens as a result of improved infiltration. Although careful application of PAM at prescribed rates can partially mitigate its negative effects, the effects of PAM application on water quality and wildlife are still unknown.

Questions have arisen as to PAM's environmental toxicity. Anionic PAM, the form found most often in erosion control products, has not been proven to be toxic to aquatic, soil, or plant species. The molecule is too large to cross membranes, so it is not absorbed by the gastrointestinal tract, is not metabolized, and does not bioaccumulate in living tissue. Cationic PAM, although not often used for erosion control applications, has been shown to be toxic to fish because of its affinity to anionic hemoglobin in the gills. Most of the concern for PAM toxicity has arisen because of acrylamide (AMD), the monomer associated with PAM and a contaminant of the PAM manufacturing process. AMD has been shown to be both a neurotoxin and a carcinogen in laboratory experiments. Current regulations require that AMD not exceed 0.05 percent in PAM products. Although there seems to be little risk from AMD as a result of prescribed application of PAM, it is uncertain what effects might result from spills, overapplication, or other accidents.

The environmental benefits of PAM are described in Table 2.4. PAM's potential detrimental effects on the environment and crop production are summarized in Table 2.5.

Table 2.4 PAM's Beneficial Effects on the Environment and Crop Production

What PAM Does	Environmental Benefit
Decrease sediment loading	Decrease turbidity Improve clarity Decrease P, N, pesticides, salts, pathogens Decrease BOD, eutrophication Decrease weed seed in runoff
Improve soil tilth	Increase infiltration Decrease runoff
Binds fine soil particles	Decrease wind erosion Accelerates clarification of turbid water bodies Prevents erosion
Increase soil water storage	Improves irrigation efficiency Decrease plant stress Improve plant vigor

Source: Sojka and Lentz, 1996.

Table 2.5 PAM's Potential Detrimental Effects on the Environment and Crop Production

What PAM Does	Potential Detrimental Effect	Preventative Measures
Increased infiltration	At prescribed rates on fine or medium textured soil, PAM can increase infiltration comparable to no-till, risking drainage and leaching of nutrient or chemicals.	Increase irrigation flow rate to prevent over-irrigation of the near end of the field.
Reduce infiltration	Over-application of PAM, or use on coarse textured soil, can reduce infiltration.	Careful application suited to site-specific needs.
Unknown effects on fish and wildlife	While safe at prescribed rates, large spills or excessive application may affect habitat.	Take care to avoid spills; use as directed.

Source: Dawson et al., 1996 in Sojka and Lentz, 1996; Sojka, personal communication, 1999.

Over 10 years of research and use have shown that PAM is an effective erosion control technology and have resulted in the agricultural application of a million acres of PAM use annually since 1998, with no reports of adverse environmental consequences. PAM has been shown to prevent the entry of sediment, nutrients, and pesticides into riparian waters via irrigation runoff and return flows. However, applicators need to be well informed of PAM properties and application requirements. Although PAM is an important additional erosion-combating conservation tool that can often be effective where other approaches fail, it should not be used as a substitute for good management and a balanced and effective conservation plan. PAM cannot make up for failure to implement effective overall conservation practices and environmentally responsible management, but can provide essential erosion protection in many situations where other solutions have proven uneconomical or ineffective.

Minton and Benedict (1999) examined the use of polymers to clarify construction site runoff that had been detained on-site. The study was undertaken because traditional management practices did not reduce turbidity and sediments to the level desired by the city of Redmond, Washington, or to the level required to meet receiving water standards of the state of Washington, especially since several streams within the city limits had salmon fisheries. When construction or repair activities must be done close to sensitive areas around a dam or during critical times for sensitive aquatic life, chemical coagulation may be an appropriate protective measure.

Minton and Benedict used a multi-phase system to remove sediments and associated pollutants from construction site runoff. The first phase involved collection of storm water at interception points. The collected runoff was then diverted, usually by pumping, to one or more storage ponds. The water was then pH-adjusted to optimize flocculation, based on the particular polymer used. Finally, the water was pumped to one of two treatment cells. During pumping, the polymer was added upstream of the transfer pump to maximize mixing and flocculation.

Two treatment cells were used so that settling could take place in one cell while runoff was pumped into the second cell. The floc was allowed to settle for a few hours to several days, with the most common practice being an overnight settling period. The duration of settling depended on the need to clear a treatment cell for treatment of more runoff water.

Table 2.6 presents performance data for the six sites studied. Median turbidities of the untreated storm water varied between sites. These differences might have been caused by differences in the percentage of soil fines, the slopes, and the application of standard management practices.

Table 2.6. Summary of Operating Performance Data for Six Test Sites (Minton and Benedict, 1999)[a]

Site	Polymer Dosage		Influent Turbidity		Effluent Turbidity		pH Control	
	Range	Median	Range	Median	Range	Median	Range[b]	Median[c]
1	25–250	75	12–2,960	200	1–45	6	45%	acid
2	10–200	100	31–4,700	2,000	1.9–39	11	16%	both
3	50–>100	100	12.9–900	150	0.5–45	7	18%	soda ash
4	50–200	100	8–4,000	400	<1–32.5	6	0%	–
5	300–400	350	2,780–17,000	14,000	0.8–23	8	97%	soda ash
6	85–140	110	17–6,650	117	1.7–18	4	85%	both

[a] Excludes the start-up period when effluent turbidities were not yet at desired levels (usually a week or two for most sites).
[b] Approximate percentage of the number of operating days on which pH adjustment occurred.
[c] Most frequent form of pH adjustment: soda ash or sulfuric acid.

Use Wildflower Cover

Because of the hardy drought-resistant nature of wildflowers, they may be more beneficial as an erosion control practice than turf grass. Though not as dense as turfgrass, wildflower thatches and associated grasses are expected to be as effective in erosion control and contaminant absorption. An additional benefit of wildflower thatches is that they provide habitat for wildlife, including insects and small mammals. Because thatches of wildflowers do not need fertilizers, pesticides, or herbicides and watering is minimal, implementation of this practice may result in cost savings. A wildflower stand requires several years to become established, but maintenance requirements are minimal once established. Prices vary greatly, from less than $15 (Stock Seed Farms, n.d.) to $40 (Albright Seed Company, 2002) a pound, for wildflower seed mixes. The amount of wildflower seeds applied depends on the desired coverage of wildflowers. However, Stock Seed Farms recommends that one pound of seed can cover 3,500 ft^2 (Stock Seed Farms, n.d.).

Designate and Reinforce Construction Entrances

A construction entrance is a pad of gravel or rock over filter cloth located where traffic enters and leaves a construction site. As construction vehicles drive over the gravel, mud and sediment are collected from the vehicles' wheels. To maximize the effectiveness of this practice, the rock pad should be at least 50 feet long and 10 to 12 feet wide. The gravel should be 1- to 2-inch aggregate 6 inches deep laid over a layer of filter fabric. Maintenance might include pressure washing the gravel to remove accumulated sediments and adding more rock to maintain adequate thickness. Runoff from this entrance should be treated before exiting the site. This practice can be combined with a designated truck wash-down station to ensure sediment is not transported off-site.

Runoff Control

To prevent the entry of sediment used during construction into surface waters, these precautionary steps should be followed:

- Identify areas with steep slopes, unstable soils, inadequate vegetation density, insufficient drainage, or other conditions that give rise to a high erosion potential.
- Identify measures to reduce runoff from such areas if disturbance of these areas cannot be avoided (Hynson et al., 1985).

Runoff diversions are structures that channel upslope runoff away from erosion source areas, divert sediment-laden runoff to appropriate traps or stable outlets, or capture runoff before it leaves the site, diverting it to locations where it can be used or released without erosion or flood damage. Diversions can be either temporary or permanent in nature.

Runoff control measures, mechanical sediment control measures, grassed filter strips, mulching, and/or sediment basins could be used to control runoff from the construction site. Scheduling construction during drier seasons, exposing areas for only the time needed for completion of specific activities, and avoiding stream fording also help to reduce the amount of runoff created during construction.

The largest surface water pollution problem during construction is suspended sediment resulting from aggregate processing, excavation, and concrete work. Preventing the entry of these materials above and/or below a dam is always the preferable alternative because runoff due to these types of construction activities can add more sediment to a reservoir, harm aquatic life above and below the dam, or affect habitat in streams below a dam. Filtration and gravitational settling during detention are the main processes used to remove sediment from construction site runoff. Methods used to control runoff and associated sedimentation from construction sites include:

Preserving Onsite Vegetation

This practice retains soil and limits runoff. The destruction of existing onsite vegetation can be minimized by initially surveying the site to plan access routes, locations of equipment storage areas, and the location and alignment of the dam. Construction workers can be encouraged to limit activities to designated areas. Reducing the disturbance of vegetation also reduces the need for revegetation after construction is completed, including the required fertilization, replanting, and grading that are associated with revegetation. Additionally, as much natural vegetation as possible should be left next to the waterbody where construction is occurring. This vegetation provides a buffer to reduce the NPS pollution effects of runoff originating from areas associated with the construction activities.

Install Vegetated Filter Strips

Vegetated filter strips are low-gradient vegetated areas that filter overland sheet flow. Runoff must be evenly distributed across the filter strip. Channelized flows decrease the effectiveness of filter strips. Level spreading devices are often used to distribute the runoff evenly across the strip (Dillaha et al., 1989).

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. These 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. For more information on vegetated filter strips, refer to EPA's *National Management Measures to Protect and Restore Wetlands and Riparian Areas for the Abatement of Nonpoint Source Pollution* (USEPA, 2005b).

Use Vegetated Buffers

Like filter strips, vegetated buffers provide a physical separation between a construction site and a waterbody. The difference between a filter strip and a vegetated buffer area is that a filter strip is an engineered device, whereas a buffer is a naturally occurring filter system. 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 (Welsch, n.d.). Preservation of vegetation for a buffer can be planned before any site-disturbing activities begin so as to minimize the impact of construction activities on existing vegetation. Trees can be clearly marked at the dripline to preserve them and to protect them from ground disturbances around the base of the tree.

Proper maintenance of buffer vegetation is important. Maintenance requirements depend on the plant species chosen, soil types, and climatic conditions. Maintenance activities typically include fertilizing, liming, irrigating, pruning, controlling weeds and pests, and repairing protective markers (e.g., fluorescent fences and flags).

Use Sediment Traps

Sediment traps are small impoundments that allow sediment to settle out of runoff water. They are typically installed in a drainage way or other point of discharge from a disturbed area. Temporary diversions can be used to direct runoff to the sediment trap. Sediment traps are ideal for sites 1 acre and smaller and should not be used for areas greater than 5 acres. They typically have a useful life of approximately 18 to 24 months. A sediment trap should be designed to maximize surface area for infiltration and sediment settling. This design increases the effectiveness of the trap and decreases the likeliness of backup during and after periods of high runoff intensity. The approximate storage capacity of each trap should be at least 1,800 ft^3/acre of disturbed land draining into the trap (Smolen et al., 1988).

Install Sediment Fence (Silt Fence) / Straw Bale Barrier

Silt fence, also known as filter fabric fence, is available in several mesh sizes from many manufacturers. Sediment is filtered out as runoff flows through the fabric. Such fences should be used only where there is sheet flow (no concentrated flow), and the maximum drainage area to the fence should be 0.5 acre or less per 100 feet of fence. To ensure sheet flow, a gravel collar or level spreader can be used upslope of the fence. Many types of fabrics are available commercially. The characteristics that determine a fence's effectiveness include filtration efficiency, permeability, tensile strength, tear strength, ultraviolet resistance, pH effects, and creep resistance. The longevity of silt fences depends heavily on proper installation and maintenance. CWP (1997d) identified several conditions that increase the effectiveness of silt fences:

- The length of the slope does not exceed 50 feet for slopes of 5 to 10 percent, 25 feet for slopes of 10 to 20 percent, or 15 feet for slopes greater than 20 percent.
- The silt fence is aligned parallel to the slope contours.
- The edges of the silt fence are curved uphill, which does not allow flow to bypass the fence.
- The contributing length to the fence is less than 100 feet.
- The fence has reinforcement if receiving concentrated flow.
- The fence was installed above an outlet pipe or weir.
- The silt fence is down slope of the exposed area.
- The silt fence alignment considers construction traffic.
- Sediment is not allowed to accumulate behind the silt fence, which increases capacity and decreases breach potential.
- The alignment of the silt fence mirrors the property line or limits of disturbance and also reflects ESC needs.

These conditions can be avoided with proper siting, installation, and maintenance. Silt fences typically have a useful life of approximately 6 to 12 months. Costs of silt fencing can vary from $0.45 a liner foot (including installation labor) (Tommy Silt Fence Machine, n.d.) to $3.73 a linear foot for hay bale/black plastic silt fencing combination use (including installation as well as removal and disposal costs) (BioFence, n.d.).

Use Sediment Basins / Rock Dams

An earthen or rock embankment located to capture sediment from runoff and retain it on the construction site.

Sediment basins, also known as silt basins, are engineered impoundment structures that allow sediment to settle out of the urban runoff. They are installed prior to full-scale grading and remain in place until the disturbed portions of the drainage area are fully stabilized. They are generally located at the low point of sites, away from construction traffic, where they will be able to trap sediment-laden runoff. Basin dewatering is achieved either through a single riser and drainage hole leading to a suitable outlet on the downstream side of the embankment or through the gravel of the rock dam. In both cases, water is released at a substantially slower rate than would be possible without the control structure.

The following are general specifications for sediment basin design criteria as presented in Schueler (1997):

- Provide 1,800 to 3,600 ft^3 of storage per contributing acre (a number of states, including Maryland, Pennsylvania, Georgia, and Delaware, recently increased the storage requirement to 3,600 ft^3 or more [CWP, 1997b]).
- Surface area equivalent to 1 percent of drainage area (optional, seldom required).
- Riser with spillway capacity of 0.2 ft^3/s/ac of drainage area (peak discharge for 2-year storm with 1-foot freeboard).
- Length-to-width ratio of 2 or greater.
- Basin side slopes no steeper than 2:1 (h:v).
- Safety fencing, perforated riser, dewatering (optional, seldom required).

Sediment basins can be classified as either temporary or permanent structures, depending on the length of service of the structure. If they are designed to function for less than 36 months, they are classified as temporary; otherwise, they are considered permanent. Temporary sediment basins can also be converted into permanent runoff management ponds. When sediment basins are designed as permanent structures, they must meet all standards for wet ponds. It is important to note that even the best-designed sediment basin seldom exceeds 60 to 75 percent total suspended solids (TSS) removal, which should be considered when selecting a sediment control practice.

Basins are most commonly used at the outlets of diversions, channels, slope drains, or other runoff conveyances that discharge sediment-laden water (see Figure 2.4, FISRWG, 1998).

Intercept Runoff Above Disturbed Slopes and Convey it to a Permanent Channel or Storm Drain

Earth dikes, perimeter dikes or swales, or diversions can be used to intercept and convey runoff from above disturbed areas to undisturbed areas or drainage systems. An earth dike is a temporary berm or ridge of compacted soil that channels water to a desired location. A perimeter dike/swale or diversion is a swale with a supporting ridge on the lower side that is constructed from the soil excavated from the adjoining swale (Delaware DNREC, 2003). These practices can be used to intercept flow from denuded areas or newly seeded areas and to keep clean runoff away from disturbed areas. The structures can be stabilized within 14 days of installation. A pipe slope drain, also known as a pipe drop structure, is a temporary pipe placed from the top of a slope to the bottom of the slope to convey concentrated runoff down the slope without causing erosion (Delaware DNREC, 2003).

Construct Benches, Terraces, or Ditches at Regular Intervals to Intercept Runoff on Long or Steep, Disturbed, or Man-Made Slopes

Benches, terraces, or ditches break up a slope by providing areas of low slope in the reverse direction. This keeps water from proceeding down the slope at increasing volume and velocity. Instead, the flow is directed to a suitable outlet or protected drainage system. The frequency of benches, terraces, or ditches will depend on the erodibility of the soils, steepness and length of the slope, and rock outcrops. This practice can be used if there is a potential for erosion along the slope.

Use Retaining Walls

Often retaining walls can be used to decrease the steepness of a slope. If the steepness of a slope is reduced, the runoff velocity is decreased and, therefore, the erosion potential is decreased.

Use Check Dams

Check dams are small, temporary dams constructed across a swale or channel. They can be constructed using gravel, rock, gabions, or straw bales. They are used to reduce the velocity of concentrated flow and, therefore, to reduce erosion in a swale or channel.

Management Measure for Chemical and Pollutant Control at Dams

Management Measure
1) Limit application, generation, and migration of toxic substances. 2) Ensure the proper storage and disposal of toxic materials. 3) Apply nutrients at rates necessary to establish and maintain vegetation without causing significant nutrient runoff to surface waters.

A. Introduction

This management measure is intended to be applied to the construction of new dams, as well as to construction activities associated with the maintenance of dams. This management measure addresses fuel and chemical spills associated with dam construction, as well as concrete washout and related construction activities. The purpose of this management measure is to prevent downstream contamination from pollutants associated with dam construction and maintenance activities.

Although suspended sediment is the major pollutant generated at a construction site, other pollutants include:

- Petroleum products—fuels and lubricants, specifically gasoline, diesel oil, kerosene, lubricating oils, grease, and asphalt
- Pesticides—insecticides, herbicides, fungicides, and rodenticides
- Fertilizers
- Construction chemicals—acids, soil additives, and concrete-curing compounds
- Wastewater—aggregate wash water, herbicide wash water, concrete-curing water, core-drilling wastewater, or clean-up water from concrete mixers
- Solid wastes—paper, wood, metal, rubber, plastic, and roofing materials
- Garbage
- Sanitary wastes
- Cement
- Lime

This management measure was selected because most erosion and sediment control practices are ineffective at retaining soluble NPS pollutants on a construction site. Many of the NPS pollutants, other than suspended sediment, generated at a construction site are carried offsite in solution or attached to clay particles in runoff. Some metals (e.g., manganese, iron, and nickel) attach to larger sediment particles and usually can be retained onsite. Other metals (e.g., copper, cobalt, and chromium) attach to fine clay particles and have greater potential to be carried offsite. Insoluble pollutants (e.g., oils, petrochemicals, and asphalt) form a surface film on runoff water and can be easily washed away (USEPA, 1973; USEPA, 2005d; USEPA, 2002b).

Factors that influence the pollution potential of construction chemicals include:

- The nature of the construction and maintenance activity
- The physical characteristics of the construction site
- The characteristics of the receiving water

Dam construction sites are particularly sensitive areas and have the potential to severely impact surface waters with runoff containing construction chemical pollutants. Because dams are located on rivers or streams, pollutants generated at these construction sites have a much shorter distance to travel before entering surface waters. Therefore, chemicals and other NPS pollutants generated at a dam construction site should be controlled.

B. Management Practices

The management measure generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices described below can be applied successfully to implement the control of chemicals and pollutants at dams. This includes dam construction as well as routine maintenance.

Practices for Controlling Chemicals and Pollutants

The following section discusses various practices for controlling chemicals and pollutants.

Develop and Implement a Spill Prevention and Control Program

Spill procedure information can be posted, and persons trained in spill handling should be onsite or on call at all times. Materials for cleaning up spills can be kept onsite and easily available. Spills should be cleaned up immediately and the contaminated material properly disposed.

In general, a spill prevention, control, and countermeasure (SPCC) plan can include guidance to site personnel on:

- Proper notification when a spill occurs
- Site responsibility with respect to addressing the cleanup of a spill
- Stopping the source of a spill
- Cleaning up a spill
- Proper disposal of materials contaminated by the spill
- Location of spill response equipment programs
- Training program for designated on-site personnel

A periodic spill “fire drill” can be conducted to help train personnel on proper responses to spill events and to keep response actions fresh in the minds of personnel.
It is important to maintain an adequate spill and cleaning kit, which could include the following:

- Detergent or soap, hand cleaner, and water
- Activated charcoal, adsorptive clay, vermiculite, kitty litter, sawdust, or other adsorptive materials

- Lime or bleach to neutralize pesticides or other spills in emergency situations
- Tools such as a shovel, broom, and dustpan and containers for disposal
- Proper protective clothing

Case Study: Fort Benning Spill Program

Fort Benning is about 182,000 acres of river valley terraces and rolling terrain in the lower Piedmont Region of central Georgia and Alabama. Best known as a U.S Army Infantry Training School, Fort Benning includes an Airborne School, Ranger School, Infantry and Ranger Regiments, and the U.S. Army Research Institute.

The Fort Benning Installation Spill Contingency Plan (ISCP) and the Spill Prevention Control and Countermeasure Plan (SPCCP) are the tools that the Environmental Management Division Spill Program uses to comply with spill prevention regulations to protect the environment. The ISCP provides a coordinated system of response actions to remove or mitigate the effects of accidental spills or discharges. The Spill Program Manager oversees this coordination effort through the Fire Department, and all units and activities in Fort Benning. The SPCCP is a site-specific plan that identifies potential sources of oil and hazardous substances and the activities required for preventing and containing any accidental discharge.

According to the Fort Benning program, personnel should attempt to respond to a spill only when it is within their capability, and only if they are adequately trained to respond. If responding to any spill, trained personnel should:

Assess the Situation

a) Identify the type of material that has spilled
b) Identify the quantity of material spilled
c) Identify the rate of release
d) Identify the areas impacted
e) Identify if resources (personnel, absorbent material, etc.) are available to respond

REACT to spills correctly as described below:

Remove the Source: Stop the source of the release and activate emergency switches.
Envelop the Spill: Use absorbent booms or earthen dams to place around the spill; block storm drains and other drainage areas (preventing discharge to the storm drains, sewer, and water bodies).
Absorb/Accumulate: Place appropriate materials (absorbents, absorbent pads, dry sweep) on the spill.
Containerize the Hazardous Waste: Accumulate the contaminated material and place it in a container for appropriate disposal.
Transmit a Report: Make appropriate notifications.

Before any attempt to REACT, individuals should protect themselves by using personal protective equipment (goggles, gloves, and suits). Follow Material Safety Data Sheets (MSDS) guidelines. MSDSs provide information on safety procedures and the hazards associated with a specific hazardous material.

Sources:
Fort Benning Environmental Management Division. No Date. *Spill Program*. https://www.infantry.army.mil/EMD/_program_mgt/spill_program/spill.htm. Accessed December 2005.

U.S. Army Infantry Homepage. 2003. *Fort Benning Information*. https://www.benning.army.mil/infantry/. Accessed December 2005.

Control Runoff from Equipment

During construction and maintenance activities at dams, equipment and machinery can be a potential source of pollution to the surface and ground water (Figure 2.7). Thinners or solvents should not be discharged into sanitary or storm sewer systems, or surface water systems, when cleaning machinery. Use alternative methods for cleaning larger equipment parts, such as high-pressure, high-temperature water washes or steam cleaning. Equipment-washing detergents can be used and wash water appropriately discharged. Small parts should be cleaned with degreasing solvents that can be reused or recycled. Washout from concrete trucks should never be dumped directly into surface waters or into a drainage leading to surface waters but can be disposed of into:

Trucks should be washed in designated washing areas to prevent untreated wastewater from being discharged to surface or ground waters

Figure 2.7 Designated Truck Washing Area

- A designated area that will later be backfilled
- An area where the concrete wash can harden, can be broken up, and can then be placed appropriately disposed
- A location not subject to surface water runoff and more than 50 feet away from a receiving water

Establish Fuel and Maintenance Staging Areas

Proper maintenance of equipment and installation of proper stream crossings will further reduce pollution of water by these sources. Vehicles need to be inspected for leaks. To prevent runoff, fuel and maintain vehicles on site only in a bermed area or over a drip pan. Fuel tanks should be protected and have containment systems. Figure 2.8 shows a containment structure for fuel tanks, which is used to help prevent spills. Stream crossings can be minimized through proper planning of access roads. This will help to keep potential sources of pollution away from direct contact with surface waters.

Figure 2.8 Containment structure for fuel tanks help prevent spills.

Control Runoff of Pollutants

Store, cover, and isolate construction materials, refuse, garbage, sewage, debris, oil and other petroleum products, mineral salts, industrial chemicals, and topsoil to prevent runoff of pollutants and contamination of ground water.

Pesticide and Fertilizer Management

Chemicals used in dam management include pesticides (insecticides, herbicides, and fungicides) and fertilizers. Since pesticides can be toxic, they have to be mixed, transported, loaded, and applied correctly and their containers disposed properly to prevent potential nonpoint source pollution. Since fertilizers can also be toxic or can damage the ecosystem, it is important that they be handled and applied properly, according to label instructions.

Even though a limited number of applications might be made at a specific dam site, consider that throughout a watershed many sites could receive applications of fertilizers and pesticides, which can accumulate in soils and in waterbodies. Application techniques also partly determine the potential risk to the aquatic environment from infrequent applications of pesticides and fertilizers. These chemicals can directly enter surface waters through five major pathways – direct application, drift, mobilization in ephemeral streams, overland flow, and leaching. Direct application is the most important source of increased chemical concentrations and is also one of the most easily controlled.

Some more specific implementation practices for pesticide and fertilizer maintenance include:

Pesticides

- Apply pesticides and fertilizers during favorable atmospheric conditions. Do not apply pesticides when wind conditions increase the likelihood of significant drift. It is also best to avoid pesticide application when temperatures are high or relative humidity is low because these conditions influence the rate of evaporation and enhance losses of volatile pesticides.
- Ensure that pesticide users abide by the current pesticide label, which might specify whether users be trained and certified in the proper use of the pesticide; allowable use rates; safe handling, storage, and disposal requirements; and whether the pesticide may be used under the provisions of an approved State Pesticide Management Plan.
- Locate mixing and loading areas, and clean all mixing and loading equipment thoroughly after each use, where pesticide residues will not enter streams or other waterbodies.
- Dispose of pesticide wastes and containers according to state and federal laws.
- Consider the use of pesticides as only one part of an overall program to control pest problems. Integrated Pest Management (IPM) strategies have been developed to control pests without total reliance on chemical pesticides.
- Base selection of pesticide on site factors and pesticide characteristics. These factors include vegetation height, target pest, adsorption (attachment) to soil organic matter, persistence or half-life, toxicity, and type of formulation.
- Check all equipment carefully, particularly for leaking hoses and connections and plugged or worn nozzles. Calibrate spray equipment periodically to achieve uniform pesticide distribution and rate.
- Always use pesticides in accordance with label instructions, and adhere to all federal and state policies and regulations governing pesticide use.

Fertilizers

- Apply slow-release fertilizers when possible. This practice reduces potential nutrient leaching to ground water, and it increase the availability of nutrients for plant uptake.
- Apply fertilizers during maximum plant uptake periods to minimize leaching.
- Base fertilizer type and application rate on soil and/or foliar analysis.

Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat from Dam Operation, Maintenance, and Removal

Management Measure
Develop and implement a program to manage the operation of dams that includes an assessment of: 1) Surface water quality and instream and riparian habitat and potential for improvement. 2) Significant nonpoint source pollution problems that result from excessive surface water withdrawals.

A. Introduction

This management measure is intended to be applied to dam operation, maintenance, and removal activities that result in the loss of desirable surface water quality, and of desirable instream and riparian habitat.

The purpose of the management measure is to protect the quality of surface waters and aquatic habitat in the portion of rivers and streams that are impacted by dams. Operation, maintenance, and dam removal activities can be assessed to determine potential improvements in water quality and aquatic habitat. These activities, as well as actions within the watershed, that contribute NPS pollutants to an impoundment should be collectively and periodically evaluated to help identify opportunities for cost-effective change.

The overall program approach is to evaluate a set of practices that can be applied individually or in combination to protect and improve surface water quality and aquatic habitat in reservoirs, as well as in areas downstream of dams. Then, a program can be implemented using the most cost-effective operation, maintenance, and removal activities to protect and improve surface water quality and aquatic and riparian habitat.

The individual application of any particular technique, such as aeration, change in operational procedure, restoration of an aquatic or riparian habitat, or implementation of a watershed protection BMP, will, by itself, probably not improve water quality to an acceptable level within the reservoir impoundment or in tailwaters flowing through downstream areas. The individual practices discussed in this portion of the guidance will usually have to be implemented in some combination in order to improve water quality in the impoundment or in tailwaters to acceptable levels.

Case Study: Turbine Venting Used to Increase DO Below Canyon Dam

The Guadalupe–Blanco River Authority (GBRA) began construction of a hydroelectric facility at Canyon Dam on the Guadalupe River in Texas in August 1987. It was first put into service in February 1989. In 1990, a combination of practices was implemented to address low DO levels at the Canyon Dam. Turbine venting and a downstream weir were used to increase DO to acceptable levels. The concentration of DO in water entering the dam was measured at 0.5 mg/L. After passing through the turbine (but still upstream of the aeration weir), the DO concentration was raised to 3.3 mg/L. After passing through the aeration weir, the DO concentration was 6.7 mg/L.

The Water Quality Inventory prepared by the Texas Natural Resource Conservation Commission for the years from 1996 to 2001 found that the section of the Guadalupe River below Canyon Dam had DO levels that were of "no concern." GBRA also publishes monthly reports about the quality of water between Canyon Dam and the Gulf of Mexico. The reports summarize DO and several other parameters in the Guadalupe River.

Sources:
Electric Power Research Institute (EPRI). 1990. Assessments and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges. EPRI GS-7001. Aquatic Systems Engineering, Wellsboro, PA. EPRI GS-7001.

NewWaves 1988: 1(4). *GBRA to Print Monthly Index of Water Quality*. http://twri.tamu.edu/twripubs/NewWaves/v1n4/news-8.html. Accessed July 2003. [Link not active]

The Canyon Lake Information Page. 2000. *Lake level and river flow*. http://www.swf-wc.usace.army.mil/canyon/LakeFlows.htm. Accessed July 2003.

Texas Natural Resource Conservation Commission. 2002. *Draft 2002 Water Quality Inventory*. http://www.tnrcc.state.tx.us/water/quality/02_twqmar/02_305b/1812_data.pdf. Accessed July 2003.

Selection of the management measure for the protection of surface water and instream and riparian habitat was based on:

- The availability and demonstrated effectiveness of practices to improve water quality in impoundments and in tailwaters of dams.
- The level of improvement in water quality of impoundments and tailwaters that can be measured from implementation of engineering practices, operational procedures, watershed protection approaches, or aquatic or riparian habitat improvements.

Successful implementation of the management measure will generally involve the following categories of practices undertaken individually or in combination to improve water quality and aquatic and riparian habitat in reservoir impoundments and in tailwaters:

- Artificial destratification and hypolimnetic aeration of reservoirs with deep withdrawal points that do not have multilevel outlets to improve DO levels in the impoundment and to decrease levels of other types of NPS pollutants, such as manganese, iron, hydrogen sulfide, methane, ammonia, and phosphorus in reservoir releases.

- Aeration of reservoir releases, through turbine venting, injection of air into turbine releases, installation of reregulation weirs, use of selective withdrawal structures, or modification of other turbine start-up or pulsing procedures.

- Providing both minimum flows to enhance the establishment of desirable instream habitat and scouring flows as necessary to maintain instream habitat.

- Establishing adequate fish passage or alternative spawning ground and instream habitat for fish species.

- Improving watershed protection by installing and maintaining BMPs in the drainage area above the dam to remove phosphorus, suspended sediment, and organic matter and otherwise improve the quality of surface waters flowing into the impoundment.

- Removing dams, which are unsafe, unwanted, or obsolete, after careful consideration of alternatives.

Case Study: Dissolved Oxygen Levels Improve Below Norris Dam

A combination of practices, consisting of a stream flow reregulation weir and a vacuum breaker turbine venting system, were implemented at Norris Dam in the Clinch River in Tennessee. The hypolimnetic discharges from the Norris Dam reservoir are chronically low in DO. To maintain a flow of 200 cfs, a reregulation weir was installed in 1984 approximately two miles downstream of the dam. In the 1980s, the turbines were fit with a hub baffle system to improve DO concentrations. The baffles induce enough air to add 2 mg/L to 4 mg/L of DO to the discharge, while reducing turbine efficiency less than 0.5 percent. The downstream weir retains part of the discharge from the turbines when they are not in operation to sustain a stream flow of about 200 cubic feet per second (cfs). Prior to these improvements, the tailwaters of the Norris Dam had DO levels below 6 mg/L an average of 131 days per year and DO levels below 3 mg/L an average of 55 days per year. After installation of the turbine venting system and reregulation weir, DO levels were below 6 mg/L only 55 days per year and were above 3 mg/L at all times.

Between 1995 and 1996 both turbines were replaced with a more efficient autoventing system, which maintains the DO concentration at about 6 mg/L. In addition, the downstream weir was upgraded in 1995 to increase its holding capacity and improve public access.

While improvements have been made to the tail water releases below Norris Dam, as of 2001 continued monitoring has shown that DO levels remain the most significant ecological health issue for Norris Reservoir. DO rated poor at all three monitoring locations because the lower half of the water column contained little oxygen (less than 2 mg/L) from late summer through early autumn. This chronic problem is mostly the result of the reservoir's basic characteristics. Norris Reservoir is a deep tributary storage reservoir with a long summer retention time; that is, it can take more than 200 days for water to move through the reservoir. As the summer sun shines on the surface of the reservoir, a warmer layer of water forms on top of a cooler layer. As a result, the layers do not mix, causing the bottom layer to become devoid of oxygen as it is used up by decaying plants and other materials that settle to the bottom. While the DO levels remain poor for the water that lies within Norris Reservoir, the equipment installed in the 1980s and 1990s adds some oxygen to the water as it passes through Norris Dam and travels downstream. Improvements in DO and minimum flows have improved the trout carrying capacity and trout health as well as the abundance and distribution of benthic invertebrates in the Clinch River. As of 2003, the Norris tailwater supports a 22.5-km (14-mi) fishery for rainbow (*O. mykiss*) and brown trout (*Salmo trutta*) before entering Melton Hill Reservoir.

Sources:
Electric Power Research Institute (EPRI). 1990. Assessments and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges. EPRI GS-7001. Aquatic Systems Engineering, Wellsboro, PA. EPRI GS-7001.

TVA. 1988. The Tennessee Valley Authority's Nonpoint Source Pollution. Control Activities Under the Memorandum of Understanding Between the State of Tennessee and the Tennessee Valley Authority During Fiscal Years 1983-1986. Tennessee Valley Authority.

TVA. No Date. Norris Reservoir. http://www.tva.gov/environment/ecohealth/norris.htm#02. Accessed May 2003.

Tennessee Wildlife Resources Agency. 2000. *Management Plan for the Norris Tailwater Trout Fishery 2002-2006*. http://www.tennessee.gov/twra/fish/StreamRiver/tailtrout/Norris.pdf. Accessed July 2003.

B. Management Practices

The management measure generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. Management practices for improving water quality associated with the operation and maintenance of dams can be categorized as:

> **Management Practices**
>
> Management practices to protect surface water quality and instream and riparian habitat are discussed in the following subsections:
>
> - Improving Water Quality
>   - Watershed Practices
>   - Aeration of Reservoir Water
>   - Aeration of Reservoir Releases
> - Improving Aquatic Habitat
> - Maintaining Fish Passage
> - Dam Removal

- Watershed Protection Practices – activities to reduce NPS pollution that take place within the watershed surrounding a dam. Reduced NPS pollutant inputs, such as sediment or nutrients, can have a significant, positive effect on water quality within a reservoir and often in reservoir releases, as well.

- Practices for Aeration of Reservoir Water – aeration activities within the reservoir. The primary goal for aerating a large portion of reservoir water is to increase oxygen levels throughout the reservoir. Other water quality factors may also improve, including levels of dissolved metals and nutrients, destratification of the water column, and improved oxygen levels in releases.

- Practices for Aeration of Reservoir Releases – a variety of aeration techniques for improving water quality, specifically dissolved oxygen levels, are presented.

Additional management practices for improving aquatic habitat and maintaining fish passage are also described. There is also a subsection on dam removal that includes planning and evaluation considerations, descriptions of the removal process, permitting requests, sediment removal techniques, descriptions of changes associated with dam removal, and a discussion of potential biological impacts.

Practices for Improving Water Quality

Achievement of desired DO levels at specific projects may require evaluation of several different technologies and management activities. The U.S. Army Corps of Engineers created a computer-modeling program, AERATE, that performs calculations to evaluate several reservoir aeration techniques. The program considers the following aeration techniques: improving water quality in the reservoir, modifying the withdrawal outlet location (and thereby changing which water is withdrawn and released from the reservoir), treating the release water to eliminate the poor quality as the flow passes through the outlet structure, and treating the release water in the tail water area (Wilhelms and Yates, 1995).

Watershed Protection Practices

Many nonpoint source pollution problems in reservoirs and dam tailwaters frequently result from sources in the contributing watershed (e.g., sediment, nutrients, metals, and toxics). Management of pollution sources from a watershed has been found to be a cost-effective solution for improving reservoir and dam tailwater water quality (TVA, 1988). Watershed protection practices can be effective in producing long-term water quality benefits and lack the high operation and maintenance costs associated with structural controls.

> Additional information about watershed protection, specifically developing and implementing watershed plans, is available from EPA's draft *Handbook for Developing Watershed Plans to Restore and Protect Our Waters*. The handbook is available at http://www.epa.gov/nps.

Watershed protection is a technique that provides long-term water quality benefits, and many states and local communities have adopted this practice. Numerous state and local governments have already legislated and implemented detailed watershed planning programs that are consistent with this management measure. For example, Oregon, New Jersey, Delaware, and Florida have passed legislation that requires county and municipal governments to adopt comprehensive plans, including requirements to direct future development away from sensitive areas. Many municipalities and regions have adopted land use and growth controls, including the towns of Amherst and Norwood and the Cape Cod region of Massachusetts; Narragansett, Rhode Island; King County, Washington; and many others.

Watershed protection management practices fall under the following four categories:

- Identifying critical conservation areas and preserving environmentally significant areas – entails identifying properties that if preserved or enhanced could maintain or improve water quality and reduce the impacts of urban runoff, as well as, preserving environmentally significant areas (includes land acquisition, easements, and development restrictions of various types).
- Identifying and addressinh nonpoint source pollution contributions – involves identifying potential upstream sources of nonpoint source pollution, as well as, providing solutions to minimize those impacts.
- Establishing and protecting stream buffers – describes important steps for protecting or establishing riparian buffer zones to enhance water quality and pollutant removal.
- Encouraging development for waterbody and natural drainage protection – includes descriptions and applications of zoning techniques that can be used to limit development density or redirect density to less environmentally sensitive areas.

Identify Critical Conservation Areas and Preserve Environmentally Significant Areas

Protection of sensitive areas and areas that provide water quality benefits (e.g., natural wetlands and riparian areas) is integral to maintaining or minimizing the impacts of development on receiving waters and associated habitat. Without a comprehensive planning approach that includes the use of riparian buffers, open space, bioretention, and structural controls to maintain the predevelopment hydrologic characteristics of the site, significant water quality and habitat impacts are likely. The experience of various communities has shown that the use of structural controls in the absence of adequate local land use planning and zoning often does not adequately protect water quality and might even cause detrimental effects, such as increased temperature.

An initial step for incorporating targeted land conservation into a runoff management program is to identify critical conservation areas on a watershed map and superimpose this information on a tax map. Owners of potential conservation lands could include a mix of individuals, corporations or other business entities, homeowner associations, government agencies, and land trusts.

Land conservation includes more than simply preserving land in its current state. It also means that an individual or organization should take responsibility for restoration of areas of the property that are contributing to runoff problems or have been adversely affected by runoff. Stewardship activities for land conservation might include:

- Resource monitoring
- General maintenance
- Control of exotic species
- Installation of structural runoff management practices

There are several options for landowners who would like to retain ownership of the parcel but relinquish stewardship and conservation management to another organization. These nonexclusive management options, discussed below, include establishing conservation easements, leases, deed restrictions, covenants, or transfer of development rights (TDRs).

Conservation Easements
A conservation easement is a legal agreement that transfers specific rights concerning the use of land by sale or donation to a government agency (municipal, county, or state), a qualified nonprofit organization (e.g., land trust or conservancy), or other legal entity without transferring title of the land (Cwikiel, 1996).

Leases
Even though government agencies, land trusts, and other nonprofit organizations would prefer that conservation lands be acquired by donation or that conservation easements be placed on the property, some lands hold so much value as conservation areas that leasing is worth the expense and effort. Leasing a property allows the agency, trust, or organization to actively manage the land for conservation.

Deed Restrictions
Restrictions can be included in deeds for the purpose of constraining use of the land. In theory, deed restrictions are designed to perform functions similar to those of conservation easements. In practice, however, deed restrictions have proven to be much weaker substitutes because unlike conservation easements, deed restrictions do not necessarily designate or convey oversight responsibilities to a particular agency or organization to enforce protection and maintenance provisions. Also, deed restrictions can be relatively easy to modify or vacate through litigation. Modifying or nullifying an easement is difficult, especially if tax benefits have already been realized. For these reasons, conservation easements are generally preferred over deed restrictions.

Covenants
A covenant is similar to a deed restriction in that it restricts activities on a property, but it is in the form of a contract between the landowner and another party. The term *mutual covenants* is used to describe a situation where one or more nearby or adjacent landowners are contracted and covered by the same restrictions.

Transfer of Development Rights (TDRs)
The concept of TDRs as a watershed protection tool is based on the premise that ownership of land includes a "bundle" of property rights. One of these rights is the right to develop the property to its "highest and best use." Although this right can be restricted by zoning building codes, environmental constraints, and other types of restrictions, the basic right to develop remains. A TDR system creates an opportunity for property owners to transfer development potential or density at one property, called a sending area to another property, called a receiving area. In the context of watershed planning objectives, TDR programs can be an effective way to transfer development potential from sensitive subwatersheds to subwatersheds that can better deal with increased imperviousness.

Identify and Address NPS Contributions

Another watershed protection practice involves the evaluation of the total NPS pollution contributions in the watershed. NPS contributions can stem from different land use activities upstream from a dam. For example, the analysis and interpretation of stereoscopic color infrared aerial photographs can be used to find and map specific areas of concern where a high probability of NPS pollution exists from septic tank systems, animal wastes, soil erosion, and other similar types of NPS pollution (TVA, 1988). Other remote sensing techniques, such as analysis of satellite imagery, can be used to map areas of concern within a watershed. Historically, TVA has used analysis of aerial photography images to survey about 25 percent of the Tennessee Valley to identify sources of nonpoint pollution in a period of less than 5 years at a cost of a few cents per acre (TVA, 1988). Modern geographic information systems (GIS) enable watershed planners and modelers to rapidly assess large watersheds in a cost-effective manner.

The development of Total Maximum Daily Loads (TMDLs) in watersheds with impaired waterbodies is a way to identify all sources of pollution. TMDLs are planning documents that provide load allocations, for both point and nonpoint sources, and identify potential contributions of pollutants to an impaired waterbody. TMDLs often include the involvement of stakeholders throughout the watershed, in not only the development, but also with implementation of specific activities within the watershed. TMDL documents can provide a plan for addressing pollution sources throughout a watershed.

Different practices can be used to control NPS pollution once sources have been identified. These practices may include the following:

Soil Erosion Control
Soil erosion has been determined to be the major source of suspended solids, nutrients, organic wastes, pesticides, and sediment that combined form the most problematic form of NPS pollution (TVA, 1988). Soil erosion and runoff controls have been addressed throughout earlier management measures in this document.

Mine Reclamation
Abandoned mines may have the potential to contribute significant sediment, metals, acidified water, and other pollutants to reservoirs (TVA, 1988). Old mines need to be located and reclaimed to reduce NPS pollutants emanating from them. Revegetation is a cost-effective method of reclaiming denuded strip-mined lands, and agencies such as the

Natural Resource Conservation Service can provide technical insight for revegetation practices.

Animal Waste Control

A major contributor to reservoir pollution in some watersheds is waste from animal confinement facilities. TVA (1988) estimated that in the Tennessee Valley, farms produced about six times the organic wastes of the population of the valley. EPA also has available the *National Management Measures to Control Nonpoint Source Pollution from Agriculture*, EPA 841-B-03-004 (http://www.epa.gov/owow/nps/pubs.html), which is a technical guidance and reference document for use by state, local, and tribal managers in the implementation of nonpoint source pollution management programs. It contains information on a variety of practices and management strategies for reducing pollution of surface and ground water from agriculture (USEPA, 2003b).

Correcting Failing Septic Systems

The objective of this practice is to protect waterbodies from pollutants discharged by OSDS. They should be sited, designed, and installed so that impacts to waterbodies will be reduced to the extent practicable. Factors such as soil type, soil depth, depth to water table, rate of sea level rise, and topography should be considered. The installation of OSDS should be prevented in areas where soil absorption systems will not provide adequate treatment of effluents containing solids, phosphorus, pathogens, nitrogen, and nonconventional pollution prior to entry into surface waters and ground water. Setbacks, separation distances, and maintenance requirements should be established.

Failing septic tank or onsite sewage disposal systems (OSDS) are another source of NPS pollution in reservoirs. TVA has found septic tank failures to be a problem in some of its reservoirs and has identified them through an aerial survey (TVA, 1988). Additional guidance on OSDS is available from EPA's *Onsite Wastewater Treatment Systems Manual* (EPA 625-R-00-008), which is available through EPA's National Service Center for Environmental Publications (http://www.epa.gov/ncepihom).

Land Use Planning

Land use plans that establish guidelines for permissible uses of land within a watershed serve as a guide for reservoir management programs addressing NPS pollution (TVA, 1988). Watershed land use plans identify suitable uses for land surrounding a reservoir, establish sites for economic development and natural resource management activities, and facilitate improved land management (TVA, 1988). Land use plans must be flexible documents that account for the needs of the landowners, state and local land use goals, the characteristics of the land and its ability to support various uses, and the control of NPS pollution (TVA, 1988).

Comprehensive planning is an effective nonstructural tool to control nonpoint source pollution. Where possible, growth should be directed toward areas where it can be sustained with minimal impact on the environment (Meeks, 1990). Poorly planned growth and development have the potential to degrade and destroy natural drainage systems and surface waters (Mantell et al., 1990). Proper planning and zoning decisions allows water quality managers to direct development and land disturbance away from areas that drain to sensitive waters. Land use designations and zoning laws can also be used to protect environmentally sensitive areas such as riparian corridors and wetlands.

Case Study: Nonpoint Source Regulations for Special Protection of Delaware River Watershed

The Delaware River Basin Commission (DRBC) adopted regulations in 1994 to control NPS pollution to some of the river's most valuable waters. The Commission is comprised of a federal representative and the governors of Delaware, New Jersey, New York, and Pennsylvania. It has regulatory, planning, and management authority over the river and commission actions are binding on member states. The NPS regulations complete the Special Protection Waters regulations package, most of which were adopted by the Commission in 1992. The Special Protection regulations expand the Commission's nondegradation policy, by providing additional protection to waters with "exceptionally high scenic, recreational, ecological and/or water supply values." The overriding policy of the regulations is that no measurable change to existing water quality of the waters is allowed. A unique feature of the regulations is that existing water quality is numerically defined in the regulations. The definition of existing water quality was statistically derived from water quality monitoring data and adopted as water quality criteria, including biocriteria. The Special Protection Waters regulations affect only the Middle and Upper Delaware, but could be applied to other nominated basin waterways that meet certain criteria. The NPS control provisions of the Special Protection Waters regulations entail a three-pronged approach.

1) NPS Control Plans for New Projects: Applicants for project approval must submit and implement NPS pollution control plans for new or increased NPS loads generated in a project's new or expanded service area. If a wastewater treatment plant of 10,000 gallons per day or more is proposed to serve a new housing development, an NPS control plan for the development serviced by the plant must be implemented. Water supply projects greater than 100,000 gallons per day and other projects in the drainage area to Special Protection Waters are similarly affected. Plans must be developed using the BMP handbooks prepared by the applicable environmental agency under Section 319 of the CWA or other relevant programs. In approving the plan, the Commission may consider trade-offs between reducing potential new NPS loads and equivalent reductions in point or other NPS loads. The regulations encourage development of local NPS control ordinances and watershed NPS plans by exempting projects governed by local ordinances or watershed plans from the project plan requirement. The Commission must approve such ordinances and watershed plans, however.

2) Priority Watershed Plans: The regulations require the Commission to prioritize watersheds draining to Special Protection Waters within two years. After adoption of the priority watershed listing, the Commission, together with the applicable state environmental agency, local governments, and other participants, must develop NPS management plans for each priority watershed within five years. Adoption of the plans into the Commission's Comprehensive Plan is the final step in the watershed-planning component of the Special Protection Waters regulations. Adoption of a plan exempts projects in that watershed from the Commission's required NPS plan for individual projects.

3) Voluntary Local Planning: The NPS control regulations encourage the voluntary development of watershed NPS control plans by local governments. Plans submitted to the Commission can be incorporated into the Commission's Comprehensive Plan, thus exempting projects in that watershed from the NPS pollution control plan requirement and putting the Commission's regulatory authority behind the watershed plan. In addition to the Special Protection Waters regulations, DBRC completed a goal-based report, the New Basin Plan Development and the 2001 updated version of the commission's Comprehensive Plan. The Comprehensive Plan consists of a compilation of commission policies and approved projects. Information on an assortment of publications and regulations compiled by DRBC can be found at http://www.state.nj.us/drbc/drbc.htm.

Sources:
Albert. 1994. Nonpoint Source Regulations for Special Protection of Delaware River Watershed. *Nonpoint Source News-Notes*. http://notes.tetratech-ffx.com/newsnotes.nsf/0a22bdfe954b03e185256d18004dcccd/0caaaccb4730fdce8525662b00529053?OpenDocument. Accessed December 2005.

Delaware River Basin Commission. 2003. *DRBC*. http://www.state.nj.us/drbc/drbc.htm. Accessed July 2003.

Establish and Protect Stream Buffers

Riparian buffers and wetlands can provide long-term pollutant removal capabilities without the comparatively high costs usually associated with constructing and maintaining structural controls. Conservation or preservation of these areas is important to water quality protection. Land acquisition programs help to preserve areas considered critical to maintaining surface water quality. Adequate buffer strips along streambanks provide protection for stream ecosystems, help stabilize the stream, and can prevent streambank erosion (Holler, 1989). Buffer strips can also protect and maintain near-stream vegetation that attenuates the release of sediment into stream channels. Levels of suspended solids have been shown to increase at a slower rate in stream channel sections with well-developed riparian vegetation (Holler, 1989).

Case Study: Controlling Runoff from Nonpoint Sources in Wisconsin

On October 1, 2002, new administrative rules to address control of polluted runoff from agricultural, non-agricultural, and transportation sources in Wisconsin went into effect. The regulations require more stringent, mandatory NPS controls for urban and agricultural sources. Although voluntary NPS control programs have been in place for 20 years, participation was not sufficient enough to improve water quality. Under the new rules, farmers must meet standards for applying fertilizer, controlling soil erosion from cropland, and managing manure. Non-agricultural land uses must maintain permanent vegetative buffer areas of 50 to 75 feet around lakes, streams, and wetlands, depending on the type and classification of the waterbody. Similar buffers or retention areas are required to control runoff to nearby streams, lakes, or wetlands from new or expanded state, county, or municipal roads. Property owners who apply fertilizer to more than 5 acres of pervious surface (e.g., lawns or turf) must do so according to an application schedule based on soil tests. Rules began to take effect in 2003. The mandatory buffer requirement was controversial during the rulemaking process. To implement this rule, the Wisconsin Department of Natural Resources (DNR) agreed to develop a buffer performance standard (based on research conducted by the University of Wisconsin through 2005) by the end of 2007.

Financing the actions required to reach compliance with the new rules was also an area of concern. Financial assistance for local pollution-control efforts is available through various DNR loan and grant programs, including the Targeted Runoff Management Grant Program, Urban Nonpoint Source and Stormwater Grant Program, and the Priority Watershed and Priority Lake Program. The concern, however, is that for existing agricultural facilities and practices, performance standards and prohibitions cannot be required unless at least 70 percent of the cost of the pollution control measure is provided.

Critics contend that financing constraints could limit implementation and burden local governments, unless state grants were made available. Others question whether loopholes in the rules would exempt construction sites from installing vegetated buffers to capture runoff. If implemented successfully, however, the regulations would put Wisconsin ahead of other states on meeting standards and might provide an economic advantage in the future when other states might be struggling to meet those standards. The final rules can be viewed at http://www.dnr.state.wi.us/org/water/wm/nps/admrules.htm.

Sources:

Barrett, R. 2001, March 22. Runoff rules spark debate. *Milwaukee Journal Sentinel.* http://www.jsonline.com/news/wauk/mar01/runoff23032201a.asp?format=print. Accessed December 2005.

Sandin, J. 2001a. January 23. Rules would control foul runoff. *Milwaukee Journal Sentinel.* http://www.jsonline.com/news/metro/jan01/runoff23012201a.asp?format=print. Accessed December 2005.

Sandin, J. 2001b. February 26. Hearings target water pollution. *Milwaukee Journal Sentinel.* http://www.jsonline.com/news/metro/feb01/pollute27022601a.asp?format=print. Accessed December 2005.

Wisconsin Department of Natural Resources. 2002. *Wisconsin's Runoff Rules.* http://www.dnr.state.wi.us/org/water/wm/nps/pdf/rules/GeneralRulesPub.pdf. Accessed July 2003.

Wisconsin Department of Natural Resources. No date. *Nonpoint Source Program Redesign Initiative.* http://www.dnr.state.wi.us/org/water/wm/nps/admrules.htm. Accessed July 2003.

Stream buffers should be protected and preserved as a conservation area because these areas provide many important functions and benefits, including:

- 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

Case Study: Stream Buffer Ordinances in Apex and Cary, North Carolina

In 2000, town commissioners of Apex and Cary, in Wake County, North Carolina, agreed to set wider buffers (strips of trees, grass, or shrubs along river and stream banks) between development and streams. Buffers help protect streams from runoff and temperature changes and provide a source of organic material for stream aquatic life. Under the new ordinance, buffers must be at least 50 feet wide along intermittent streams and must average 100 feet wide along perennial streams. The towns chose to use an average rather than a strict 100-foot minimum to allow landowners flexibility. In addition to the buffer ordinance, Apex and Cary also halved the limit of impervious surfaces on a given tract of land over which retention ponds are required to control runoff (from 24 percent to 12 percent).

Following the trend set by Apex and Cary to protect surface water quality from NPS pollution, in 2001 Wake County established the Watershed Management Task Force. The Task Force compiled a report that concluded that sediment is the primary cause of degradation in most Wake County streams. The main sources of sediment are construction site runoff and streambank erosion caused by larger volumes of water running off developing areas. The report included a list of recommendations for Wake County, which includes the following:

- Require 100-foot stream buffers on perennial streams within priority watersheds and 50-foot buffers in other watersheds.
- Allow no development or filling in the 100-year floodplain, except for utilities and infrastructure.
- Allow and encourage conservation subdivisions, which preserve large tracts of open space within new subdivisions.
- If municipal water and sewer are available to a site, a minimum of 30 percent open space should be preserved to qualify as a conservation subdivision.
- Use incentives to help meet targets for less impervious surfaces in priority watersheds.
- Better educate homeowners about well and septic system maintenance.

Based on these recommendations, in 2003 the Wake County Commissioners doubled no–build zones, or buffer zones, to 100 feet along streams within water supply watersheds throughout the county. The county also banned construction within the 100-year floodplain.

Sources:
Price, J. 2000, December 7. Apex leaders agree to beef up their stream-protection measures: New rules call for larger buffers. *The Raleigh News and Observer*.

Stradling, R. 2003, April 8. Wider buffers, cleaner water. *The Raleigh News and Observer*.

Wake County Government. 2002. *Watershed Management Task Force Recommends Ways to Protect Drinking Water, Reduce Flooding and Erosion*. http://www.wakegov.com/news/wmtf111802.htm. Accessed August 2003.

Zebrowski, J. 2003, May 20. Wake commissioners adopt water quality measures. *The Raleigh News and Observer.*

Specific stream buffer practices could include:

- Establishing a stream buffer ordinance
- Developing vegetative and use strategies within management zones
- Establishing provisions for stream buffer crossings
- Integration of structural runoff management practices where appropriate
- Developing stream buffer education and awareness programs

More information on establishing and protecting stream buffers is available through Section 3 of this guidance and EPA's *National Management Measures to Control Nonpoint Source Pollution from Urban Areas* (http://www.epa.gov/owow/nps/urbanmm/index.html), a technical guidance and reference document for use by state, local, and tribal managers in the implementation of nonpoint source pollution management programs. It contains a variety of practices and management activities for reducing pollution of surface and ground water from urban areas (USEPA, 2005d).

Encourage Waterbody and Natural Drainage Protection when Siting Developments

A complete understanding of watershed protection should include the implementation of practices that guide future development and land use activities. This will not only help to identify existing sources of NPS pollution but also prevent future impairments that may impact dam construction or operations and reservoir management. Watershed protection practices can include zoning for natural resource protection. Several zoning techniques are:

- Use cluster zoning and planned unit development
- Consider resource protection zones
- Practice performance-based zoning
- Establish overlay zones
- Establish bonus or incentive zoning
- Consider large lot zoning
- Practice agricultural protection zoning
- Use watershed-based zoning
- Delineate urban growth boundaries

More details about these techniques and case studies can be found in *Protecting Wetlands: Tools for Local Governments in the Chesapeake Bay Region* (Chesapeake Bay Program, 1997).

Case Study: King County, Washington, Growth Management Initiatives

Agricultural zoning ordinances can be combined with other initiatives to promote farming and forestry and to protect rural areas from being overtaken by urban sprawl. King County, Washington, has undertaken several initiatives to promote diversity in lifestyle choices, encourage the continuation of farming and forestry, protect environmental quality and wildlife habitat, and maintain a link to the county's heritage by preserving rural areas. So far the county has reduced its development rate in rural areas from 15 percent in 1980 to 6 percent in 2002. The goal is to further reduce the development rate to 4 percent. The county issued orders to close loopholes in subdivision and land segregation regulations and tighten subdivision requirements for rural lands. These efforts will ensure that new development is consistent with current environmental and development standards.

King County strives to promote agriculture and protect farmlands. Some of the county's initiatives include maintaining an agricultural district as an "unincorporated urban area" to permanently protect this area from development pressures, establishing the Puget Sound Fresh program to promote locally grown and produced products, establishing a Farm Link program to connect farmers with land to sell or lease with those wishing to farm, and providing improved services for rural community centers. The county also established a Rural Forest Commission to encourage forestry and maintain the forestland base in the county's rural areas. The county implemented a Farmlands Preservation Program, which by 2002 had preserved 12,793 acres of agricultural lands through purchase or donation of development rights.

The Conservation Futures Tax (CFT) levy funds are collected from property taxes levied throughout King County and dedicated to the acquisition of open space in cities and rural areas. The Conservation Futures Citizens Committee makes an annual recommendation of project funding allocations to King County based on its review of project applications and site visits. The Committee's recommendations for the funds raised in 2003 and 2004 would protect over 1,000 acres of salmon and wildlife habitat, purchase over 200 acres of development rights to protect farms on city borders, and create and preserve urban Green Spaces. Additionally, the county is able to preserve hundreds more acres of rural land each year through incentive-based taxation programs.

King County's 2000 Comprehensive Plan includes the following goals and initiatives:

- Ensure that zoning complies with goals to reduce the rate of growth and protect the environment.
- Ensure that the types and scale of development in the rural area blend with traditional rural development.
- Implement recommendations from the forest commission to bolster King County's forest and farming economies.
- Consider alternative uses of agricultural land, such as for wetland mitigation or recreation, such that these uses will not harm the integrity of agriculture in the county.

More information about King County's Growth Management Initiatives can be found on the Smart Growth Rural Legacy web page at http://www.metrokc.gov/smartgrowth/rural.htm.

Source:

Sims, R. 2000. *SmartGrowth: Rural Legacy*. http://www.metrokc.gov/smartgrowth/rural.htm. Accessed June 2003.

Practices for Aeration of Reservoir Waters

Systems that have been developed and tested for reservoir aeration rely on atmospheric air, compressed air, or liquid oxygen to increase DO concentrations in reservoir waters. Mixing of reservoir water to destratify warmer, oxygen rich, epilimnion and cooler, oxygen poor, hypolimnion waters can be used. However, this practice has not been used at large hydropower reservoirs because of the associated cost in deep, large volume reservoirs.

One method for mixing reservoir water is the U-tube design, in which water from deep in the impoundment is pumped to the surface layer. The inducement of artificial circulation through aeration of the impoundment may also provide the opportunity for a “two-story” fishery, reduce internal phosphorus loading, and eliminate problems with iron and manganese in drinking water (Thornton et al., 1990).

Air injection systems operate similar to pumping systems to mix water from different strata in the impoundment, except that air or pure oxygen is injected into the pumping system. Air injection systems are categorized as partial air lift systems and full air lift systems. In the partial air lift system, compressed air is injected at the bottom of the unit; then the air and water are separated at depth and the air is vented to the surface. In the full air lift system, compressed air is injected at the bottom of the unit (as in the partial air lift system), but the air-water mixture rises to the surface. The full air lift design has a higher efficiency than the partial-air lift and has a lesser tendency to elevate dissolved nitrogen levels (Thornton et al., 1990).

Diffused air systems provide effective transfer of oxygen to water by forcing compressed air through small pores in diffuser systems to form bubbles. One diffuser system test in the Delaware River near Philadelphia, Pennsylvania in 1969-1970 demonstrated the efficiency of this practice. Coarse-bubble diffusers were deployed at depths ranging from 13 to 38 feet. Depending on the depth of deployment, the oxygen transfer efficiency varied from 1 to 12 percent. When compared with other systems discussed below, this efficiency rate is rather low. But the results of this test determined that river aeration was more economical than advanced wastewater treatment as a strategy for improving the levels of DO in the river (EPRI, 1990). Another type of oxygen injection system, which pumps gaseous oxygen into the hypolimnion through diffusers, has effectively improved DO levels in the reservoir behind the Richard B. Russell Dam (Savannah River, on the Georgia-South Carolina border). The system is operated 1 mile upstream of the dam, with occasional supplemental injection of oxygen at the dam face when DO levels are especially low. The system has successfully maintained DO levels above 6 mg/L in the releases, with an average oxygen transfer efficiency of 75 percent (EPRI, 1990; Gallagher and Mauldin, 1987).

Case Study: TVA Experiments with Pure Oxygen

Oxygen injection systems use pure oxygen to increase reservoir DO levels. One type of system pumps gaseous oxygen into the hypolimnion through diffusers. In 1988, a pilot oxygen diffuser system (20 ft by 33 ft frame supporting 78 membrane diffusers) was installed at TVA's Douglas Dam (French Broad River, TN) to improve DO levels. In 1998, DO improvements in the releases were about 2 mg/L. However, in 1989 during summer stratification, oxygen improvement in the releases dropped to nearly zero. This was attributed to oxygen demands from the reservoir sediments stirred up and mixed by the strong plumes induced by the diffusers.

After a failed attempt in 1991 to deploy a 400-foot by 100-foot PVC diffuser frame, supporting 100 50-foot long porous hoses, TVA successfully deployed 16 smaller PVC diffuser frames, measuring 100 feet by 120 feet, in 1993. These diffusers provided up to 2 mg/L of DO improvement in the 16,000 cfs peak hydropower flows of the four turbines at Douglas Dam. Although these diffusers are effective, and are still in use, the frames and buoyancy connections were too unwieldy and expensive for future designs.

Due to the high cost of building and operating this system, other options were explored. An oxygen diffuser system costs about $188/hour to achieve an oxygen uptake of 1.6 mg/L. The same oxygen uptake rate (using an aeration system with water pumps) costs about $10.50/hour to power and maintain. As a result, an aeration system with nine surface water pumps was installed at Douglas Dam between 1993 and 1994. The system moves a large volume of highly oxygenated surface water down to elevation, where it is withdrawn through the hydropower intakes. The mixture of oxygen-rich surface waters with oxygen-depleted hypolimnetic waters increases DO levels. Under average conditions the system increases DO in the tailwaters by 1.5 to 2 mg/L. A total of $2.5 million was spent on the surface water pump system (equipment cost $1.5 million and installation cost $1 million). Surface water pumps are expensive to install, but are inexpensive to maintain and operate, making them a desirable option. Three different systems (turbine venting system, surface water pumps, and an oxygen-injection system or diffuser) are currently used to improve DO in the tailwater at Douglas Dam.

TVA conducted some of the earliest research on reservoir diffuser systems for hydropower application at Fort Patrick Henry Dam (Holston River, TN). A pilot study and demonstration project were conducted from 1973 to 1976. The installation used a liquid oxygen gas supply and ceramic diffusers mounted on diffuser frames that were supported by columns extending from the reservoir bottom to the surface. Levels of DO in the tailwaters increased from near 0 mg/L to 4 mg/L from this aeration system. Unfortunately, the operation costs were relatively high. An operation system to increase DO in the discharge from both hydroturbines at Fort Patrick Henry Dam to 5 mg/L would have an initial capital cost of $400,000 and an annual operating cost of $110,000. However, these results were site-specific and every site should be evaluated for the best mix of solutions.

The pilot study provided good test data, but was discontinued due to an unrelated improvement in incoming water quality conditions at the site and a subsequent loss of project funding. As of 2003, DO levels in the water released from Fort Patrick Henry Dam are improved by operating a turbine-venting system upstream at Boone Dam. The system introduces airflow into low-pressure zones just below the turbines, which creates small air bubbles. Oxygen from the bubbles is absorbed into the oxygen-poor water as it flows through the turbines.

Sources:

Harshbarger, E.D. 1987. Recent Developments in Turbine Aeration. In Proceedings: CE Workshop on Reservoir Releases. Misc. Paper E-87-3. U.S. Army Corp of Engineers Waterways Experiment Station, Vicksburg, MS. Misc. Paper E-87-3 and TVA. 1988.

Mobley, M., W. Tyson, J. Webb and G. Brock. No date. *Surface water pumps to improve dissolved oxygen content of hydropower releases*. http://www.tva.gov/environment/pdf/rri_surfwat.pdf. Accessed July 2003.

Mobley, M. R. Ruane, and E. Harshbarger. No date. *And Then It Sank…" the development of an oxygen diffuser for hydropower*. http://www.mobleyengineering.com/publications/andthenitsank.pdf. Accessed July 2003.

Tennessee Valley Authority. No Date. Water quality improvements at tributary dams. http://www.tva.gov/environment/water/rri_triblist.htm. Accessed July 2003.

The Tennessee Valley Authority's Nonpoint Source Pollution Control Activities Under the Memorandum of Understanding Between the State of Tennessee and the Tennessee Valley Authority During Fiscal Years 1983-1986. Tennessee Valley Authority.

U.S. EPA. 2002. *Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat*. http://www.epa.gov/owow/nps/MMGI/Chapter6/ch6-3c.html>. Accessed July 2003.

The diffused air system is generally the most cost-effective method to raise low DO levels within a reservoir (Henderson and Shields, 1984). However, the costs of air diffuser operation may be high for deep reservoirs because of hydraulic pressures that must be overcome. Destratification that results from deployment of an air diffuser system may also mix nutrient-rich waters located deep in the impoundment into layers located closer to the surface, increasing the potential for stimulation of algal populations. Barbiero et al. (1996), in a study on the effects of artificial circulation on a small northeastern impoundment, found that artificial circulation ultimately had no effect on the magnitude of summer phytoplankton populations. However, the authors note that intermittent mixing events tend to promote increased transport of phosphorus into the epilimnion. While this had no effect on phytoplankton populations in the studied lake, it demonstrates the potential of artificial circulation to impact water quality and the need for careful evaluation of potential impacts.

Some older types of mechanical agitation systems operate by pumping water from the reservoir into a splash basin on shore, where it is aerated and then returned to the hypolimnion. Although these types of systems are comparatively inefficient, they have been used successfully (Wilhelms and Smith, 1981).

If the principal objective is to improve DO levels only in the reservoir releases and not throughout the entire impoundment, then aeration can be applied selectively to discrete layers of water immediately surrounding the intakes or as water passes through release structures such as hydroelectric turbines. Localized mixing is a practice to improve releases from thermally stratified reservoirs by destratifying the reservoir in the immediate vicinity of the outlet structure. This practice differs from the practice of artificial destratification, where mixing is designed to destratify all or most of the reservoir volume (Holland, 1984). Localized mixing is provided by forcing a jet of high-quality surface water downward into the hypolimnion. Pumps used to create the jet generally fall into two categories, axial flow propellers and direct drive mixers (Price, 1989). Axial flow pumps usually have a large-diameter propeller (6 to 15 feet) that produces a high-discharge, low-velocity jet. Direct drive mixers have small propellers (1 to 2 feet) that rotate at high speeds and produce a high-velocity jet. The axial flow pumps are suitable for shallow reservoirs because they can force large quantities of water down to shallow depths. The high-momentum jets produced by direct drive mixers are necessary to penetrate deeper reservoirs (Price, 1989).

Oxygen injection systems use pure oxygen to increase levels of dissolved oxygen in reservoirs. One type of design, termed side stream pumping, carries water from the impoundment onto the shore and through a piping system into which pure oxygen is injected. After passing through this system, the water is returned to the impoundment.

Practices to Improve Oxygen Levels in Tailwaters

Aeration of water as it passes through the dam or through the portion of the waterway immediately downstream from the dam is another approach to improving DO in water releases from dams. The systems in this category rely on agitation and turbulence to mix the reservoir releases with atmospheric air. One approach involves the increased use of spillways, which release surface water to prevent it from overtopping the dam. An alternative approach is to install barriers called weirs in the downstream areas. Weirs are designed to allow water to overtop them, which can increase DO through surface agitation and increased surface area contact. Some of these downstream systems create supersaturation of dissolved gases and may require additional modifications to prevent supersaturation, which may be harmful to aquatic organisms.

The quality of reservoir releases can be improved through adjustments in the operational procedures at dams. These include scheduling of releases or of the duration of shutoff periods, instituting procedures for the maintenance of minimum flows, making seasonal adjustments in the pool levels or in the timing and variation of the rate of drawdown, selecting the turbine unit that most increases DO (often increasing the DO levels by 1 mg/L), and operating more units simultaneously (often increasing DO levels by about 2 mg/L). The magnitude and duration of reservoir releases also should be evaluated to determine impacts to the salinity regime in coastal waters, which could be substantially altered from historical patterns.

Two factors should be considered when evaluating the suitability of hydraulic structures such as spillways and weirs for their application in raising the DO concentration in waterways:

- Most of the measurements of DO increases associated with hydraulic structures have been collected at low-head facilities. The effectiveness of these devices may be limited as the level of discharge increases (Wilhelms, 1988).

- The hydraulic functioning of these types of structures should be carefully considered since undesirable flow conditions may occur in some instances (Wilhelms, 1988).

Turbine Venting

Turbine venting is the practice of injecting air into water as it passes through a turbine. If vents are provided 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. In early designs, the turbine was vented through existing openings, such as the draft tube opening or the vacuum breaker valve in the turbine assembly. Air forced by compressors into the draft tube opening enriched reservoir waters with little detectable DO to concentrations of 3 to 4 mg/L. Overriding the automatic closure of the vacuum breaker valve (at high turbine discharges) increased DO by only 2 mg/L (Harshbarger, 1987).

Turbine venting uses the low-pressure region just below the turbine wheel to aspirate air into the discharges (Wilhelms, 1984). 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. 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. Hub baffles have also been added to autoventing turbines at the Norris Dam (Clinch River, Tennessee) to further improve the DO levels in the turbine releases (Jones and March, 1991).

Recent developments in autoventing turbine technology show that it may be possible to aspirate air with no resulting decrease in turbine efficiency. In one test of an autoventing turbine at the

Norris Dam, the turbine efficiency increased by 1.8 percent (March et al., 1991; Waldrop, 1992). Technologies like autoventing turbines are very site-specific and outcomes will vary considerably.

Gated Conduits

Gated conduits are hydraulic structures that divert the flow of water under the dam. They are designed to create turbulent mixing to enhance oxygen transfer. Gates are used to control the cross-sectional area of flow. Gated conduits have been extensively analyzed for their performance and effectiveness (Wilhelms and Smith, 1981), although the available data are mostly from high-head projects (Wilhelms, 1988). An example of the effectiveness found that gated conduit structures were able to achieve 90 percent aeration and a minimum DO standard of 5 mg/L (Wilhelms and Smith, 1981).

Water Conveyances

These are the open or closed channel, conduit, or drop structure used to convey water from a reservoir. The USACE has studied the performance of spillways and overflow weirs at its facilities to determine the importance of these structures in improving DO levels. For example, data have been analyzed for the test spill done in 1999 at Canyon Ferry Dam in Montana, which found that allowing a portion of the releases to go over the spillways resulted in a significant increase in DO in the river downstream of the dam. Initially the use of spillways appeared to be a viable solution to the problem of low dissolved oxygen in the river below the dam. However, there was a problem with nitrogen supersaturation.

The operation of some types of hydraulic structures has been linked to problems of the supersaturation. An unexpected fish kill occurred in spring 1978 due to supersaturation of nitrogen gas in the Lake of the Ozarks (Missouri) within 5 miles of Truman Dam, caused by water plunging over the spillway and entraining air. The vertical drop between the spillway crest and the tailwaters was only 5 feet. The maximum total gas saturation was 143 percent, which is well above desired saturation levels. In this case, the spillway was modified by cutting a notch to prevent water from plunging directly into the stilling basin (ASCE, 1986).

Spillway Modifications

Spill at hydroelectric dams is routinely required during periods of high runoff when the river discharge exceeds what can be passed through the powerhouse turbines. Spill has been associated with gas supersaturation problems. For example, the Columbia River has a series of 11 dams beginning with the Grand Coulee and ending with Bonneville. If all of these dams were spilling simultaneously, the entire river would become and remain highly saturated with nitrogen gas. The USACE has proposed several practices for solving the gas supersaturation problem. These include (1) passing more headwater storage through turbines, installing new fish bypass structures, and installing additional power units to reduce the need for spill; (2) incorporating "flip-lip" deflectors in spillway-stilling basins, transferring power generation to high-dissolved-gas-producing dams, and altering spill patterns at individual dams to minimize nitrogen mass entrainment; and (3) collecting and transporting juvenile salmonids around affected river reaches. Only a few of these practices have been implemented (Tanovan, 1987). As more attention is being paid to maintaining minimum flows in rivers for fish passage and spawning, mangers are balancing the need for spills with the potential impacts of gas supersaturation (DeHart, 2003; Van Holmes and Anderson, 2004; Anderson, 1995; USFWS, 2001). For example, the U.S. Fish and Wildlife Service has routinely monitored gas supersaturation in reaches below Bonneville Dam (Columbia River, Oregon) to protect migrating salmon, many of which are endangered species (USFWS, 2001).

Case Study: Spillways and Weirs Increase Dissolved Oxygen

Replacing obsolete structures, the Columbia and Jonesville Locks and Dams (Ouachita River, LA) opened to navigation in 1972. Each lock is 84 feet wide and 600 feet long and impounds a slack-water pool approximately 100 miles long. As water flows over a weir or spillway, atmospheric gasses (mainly nitrogen and oxygen) can dissolve into the water. Likewise, degassing of dissolved gasses in the water coming out of solution can occur at these structures. In the past, increases in DO concentration of about 2.5 mg/L and 3 mg/L were measured at the overflow weirs of the Jonesville Lock and Dam and the Columbia Lock and Dam, respectively. Passage of water through the combinations of spillways and overflow weirs at these two facilities resulted in DO saturation levels of 85 to 95 percent in downstream waters.

Despite the lock and dams ability to increase DO levels, a TMDL report was filed for the Ouachita River extending from Columbia Lock and Dam to Jonesville Lock and Dam after being placed on the Louisiana 303(d) List for not fully supporting the designated use of propagation of fish and wildlife. Water quality impairment for DO and nutrients has been attributed to agricultural activities. TMDLs have been developed for DO and nutrient allocations for nonpoint sources. In order to maintain the DO standard of 5 mg/L throughout Ouachita River from Columbia Lock and Dam to Jonesville, NPS nutrient loads will need to be reduced by approximately 49%. No treatment upgrades will be needed for point source discharges because their flows are small and they do not contribute significantly to the total oxygen demand in the stream. Although the lock and dam structures increase DO levels in the water, the NPS contributions of nutrients from the surrounding land uses continue to degrade the water quality.

Sources:
St. Anthony Falls Laboratory. No Date. *Gas Transfer at Hydraulic Structures, Chemical Fate and Transport in the Environment*. http://www.safl.umn.edu/research/basic/gulliver/page3.html. Accessed July 2003.

USEPA. 2002. *Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat*. U.S. Environmental Protection Agency. http://www.epa.gov/owow/nps/MMGI/Chapter6/ch6-3c.html. Accessed July 2003.

USEPA. EPA Region 6 Contract No. 68-C-99-249 Work Assignment #2-1082002.*Ouachita River TMDLs for Dissolved Oxygen and Nutrients.* http://www.epa.gov/region6/water/ecopro/latmdl/ouachitado(f).pdf. Accessed August 2003.

US Army Corps of Engineers. No Date. *Ouachita River Basin.* http://www.mvn.usace.army.mil/pao/bro/wat_res98/WaterRes98_5of16.pdf. Accessed August 2003.

Wilhelms, S.C. 1988. Reaeration at Low-Head Gated Structures; Preliminary Results. Water Operations Technical Support, Volume E-88-1, July 1988. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Reregulation Weir

Reregulation weirs have been constructed from stone, wood, and aggregate. In addition to increasing the levels of DO in the tailwaters, reregulation weirs result in a more constant rate of flow farther downstream during periods when turbines are not in operation. A reregulation weir constructed downstream of the Canyon Dam (Guadalupe River, Texas) increased DO levels in waters leaving the turbine from 3.3 mg/L to 6.7 mg/L (EPRI, 1990).

The USACE Waterways Experiment Station (Wilhelms, 1988) has compared the effectiveness with which various hydraulic structures accomplished the reaeration of reservoir releases. The study concluded that, whenever operationally feasible, more discharge should be passed over weirs to improve DO concentrations in releases. Results indicated that overflow weirs aerate releases more effectively than low-sill spillways (Wilhelms, 1988).

Case Study: Spillway Deflectors Help Reduce Nitrogen

Operation of some types of hydraulic structures has been linked to problems from the supersaturation of certain gases. Discharges through dams and spillways can cause high levels of dissolved gases to be entrained in the water, possibly causing supersaturation. Under nitrogen supersaturation conditions, fish can develop gas embolisms in the blood or body tissues. This is referred to as gas bubble disease and can be lethal to the fish.

In 1995, the USACE began the Lower Snake River Juvenile Salmon Migration Feasibility Study to investigate structural alterations to dams to improve the migration of juvenile Chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*Oncorhynchus nerka*) and steelhead (*Oncorhynchus mykiss*) species listed under the Endangered Species Act. The USACE selected the adaptive migration alternative, which combines a series of structural and operational measures intended to improve fish passage through the lower Snake River. The structural changes include the installation of spillway deflectors on the four dams the USACE operates on the lower Snake River including Ice Harbor, Lower Monumental, Little Goose, and Lower Granite.

Overall, spillway deflectors have been installed at seven of the eight lower Columbia and Snake dams. The deflectors are designed to direct flows horizontally into the stilling basin to prevent deep plunging and air entrainment. The spillway deflectors have been found to be the most effective means for reducing nitrogen supersaturation. By spilling water, the juvenile fish are also diverted over the dam spillway and away from turbines. For the Snake River, estimates of turbine passage mortality vary from 2 to 32 percent over a wide range of current and historic conditions. For spillway passage on the Snake River, ten of 13 juvenile fish passage studies conducted prior to 1995 found low mortality rates of 0 to 2.2 percent (most studies involved steelhead (*Oncorhynchus mykiss*) and yearling chinook salmon (*Oncorhynchus tshawytscha)*). Direct mortality due to passage through a spillway results primarily from abrasion, but juveniles could die later through indirect means, such as descaling, stress, predation, or reduced viability due to dissolved gas supersaturation. Accurate data on delayed mortality from this passage route are not available, although limited data suggest it is most likely low.

Sources:

ASCE. 1986. *Lessons Learned from Design, Construction, and Performance of Hydraulic Structures*. Hydraulic Structures Committee of the Hydraulics Division of the American Society of Civil Engineers, New York, NY.

Bonneville Power Administration. 1991. *Environmental Assessment: East Fork Salmon Habitat Enhancement Project*. Bonneville Power Administration, Portland, OR.

U.S. Environmental Protection Agency. 2002. *Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat*. http://www.epa.gov/owow/nps/MMGI/Chapter6/ch6-3c.html. Accessed July 2003.

U.S Army Corps of Engineers – Walla Walla District. 2002. *Lower Snake River Juvenile Salmon Migration Feasibility Study*. http://www.nww.usace.army.mil/lsr/default.htm. Accessed August 2003.

U.S. Army Corps of Engineers Northwestern Division. 2002. *Columbia River Basin – Dams and Salmon*. http://www.nwd.usace.army.mil/ps/colrvbsn.htm. Accessed August 2003.

Labyrinth Weir

Labyrinth weirs have extended crest length and are usually W-shaped. These weirs spread the flow out to prevent dangerous undertows in the plunge pool. A labyrinth weir at South Holston Dam was constructed for the dual purpose of providing minimum flows and improving DO in reservoir releases. The weir aerates to up to 60 percent of the oxygen deficit. For instance, projected performance at the end of the summer is an increase in the DO from 3 mg/L to 7 mg/L (or an increase of 4 mg/L) (Gary Hauser, TVA, personal communication, 1992). Actual increases in the DO will depend on the temperature and the level of DO in the incoming water.

Selective Withdrawal

Temperature control 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. Dams capable of selectively releasing waters of different temperatures can provide cooler or warmer water temperature downstream at times that are critical for other instream resources, such as during periods of fish spawning and development of fry (Fontane et al., 1981; Hansen and Crumrine, 1991). Stratified reservoirs are operated to meet downstream temperature objectives such as to enhance a cold-water or warm-water fishery or to maintain preproject stream temperature conditions. Release temperature may also be important for irrigation (Fontane et al., 1981).

Multilevel intake devices in storage reservoirs allow selective withdrawal of water based on temperature and DO levels. These devices minimize the withdrawal of surface water high in blue-green algae, or of deep water enriched in iron and manganese. Care should be taken in the design of these systems not to position the multilevel intakes too far apart because this will increase the difficulty with which withdrawals can be controlled, making the discharge of poor-quality hypolimnetic water more likely (Howington, 1990; Johnson and LaBounty, 1988; Smith et al., 1987).

Turbine Operation

Implementation of changes in the turbine start-up procedures can also enlarge the zone of withdrawal to include more of the epilimnetic waters in the downstream releases. Monitoring of the releases at the Walter F. George lock and dam (Chattahoochee River, Georgia), showed levels of DO declined sharply at the start-up of hydropower production. The severity and duration of the DO drop were found to be reduced by starting up all the generator units within a minute of each other (Findley and Day, 1987).

Computer Modeling

A useful tool for evaluating the effects of operational procedures on the quality of tailwaters is computer modeling. For instance, computer models can describe the vertical withdrawal zone that would be expected under different scenarios of turbine operation (Smith et al., 1987). Zimmerman and Dortch (1989) modeled release operations for a series of dams on a Georgia River and found that procedures that were maintaining cool temperatures in summer were causing undesirable decreases in DO and increases in dissolved iron in autumn. The suggested solution was a seasonal release plan that is flexible, depending on variations in the in-pool water quality and predicted local weather conditions. Care should be taken with this sort of approach to accommodate the needs of both the fishery resource and reservoir recreationalists, particularly in late summer.

Modeling has also been undertaken for a variety of TVA and USACE facilities to evaluate the downstream impacts on DO and temperature that would result from changes in several operational procedures, including (Hauser et al., 1990a; Hauser et al., 1990b; Higgins and Kim, 1982; Nestler et al., 1986b):

- Maintenance of minimum flows
- Timing and duration of shutoff periods
- Seasonal adjustments to the pool levels
- Timing and variation of the rate of drawdown

Case Study: The Tennessee Valley Authority (TVA) Solutions

Several treatment methods can eliminate or mitigate low DO concentrations in release waters. These methods can include improving water quality in the reservoir or modifying the withdrawal outlet location, thereby changing which water is withdrawn and released from the reservoir. Other methods include treating the release water to eliminate poor quality as the flow passes through the outlet structure or treating release water in the tailwater area. These methods can be generally categorized into three areas: in-reservoir, instructure, and downstream techniques. TVA employs a variety of methods to improve water quality conditions around dams.

At Fort Loudoun Dam, TVA uses an oxygen-injection system to help maintain adequate dissolved-oxygen levels. Perforated hoses suspended above the reservoir bottom bubble gaseous oxygen into the upstream water before it is pulled into the turbines. At Watts Bar Dam, a practice of selectively using turbines to achieve desired water quality goals, called unit preference, and an oxygen injection system help meet aeration targets. During periods of low oxygen levels, TVA uses unit preference by operating the turbines nearest the banks first. These turbines typically draw in reservoir water that is higher in DO. If additional aeration is needed, an oxygen injection system is available. Oxygen can be bubbled into the water through perforated hoses suspended above the reservoir bottom. Installation of the oxygen injection system ranges from $600,000 to $2 million depending on specific site considerations. Operation of these systems at six of TVA's hydropower facilities cost between $600,000 and $900,000 annually.

In 1997, after five years of operating the oxygen injection systems at Fort Loudoun Dam, Watts Bar Dam, and eight other locations, TVA found that the systems obtained satisfactory results. The TVA test results found oxygen transfer efficiencies of 90 to 95 percent with dramatic increases in dissolved oxygen in the reservoir hypolimnion. In addition, the porous hoses have maintained their bubble pattern and have proven to be resistant to clogging and damage. Constant tailwater monitoring and frequent oxygen flow have been used by to TVA to control oxygen usage.

At the seven dams—Chickamauga, Nickajack, Guntersville, Wheeler, Wilson, Pickwick, and Kentucky—TVA provides minimum flows to help maintain adequate DO levels downstream. This is done by releasing a specified amount of water at three key locations— Chickamauga, Pickwick, and Kentucky—during different seasons of the year. Information on monitored DO levels in the reservoirs at these dams can be found online at *http://www.tva.gov/environment/ecohealth/index.htm*.

Sources:
Mobley, M. 1997. *TVA Reservoir Aeration Diffuser System*. http://www.loginetics.com/pubs/Diffuser_MHM_WP97.PDF. Accessed August 2003.

TVA. No Date. *Reservoir Ratings.* http://www.tva.gov/environment/ecohealth/index.htm. Accessed August 2003.

TVA. No Date. Tailwater Improvements, Improving Conditions Below Main-River Dams. http://www.tva.gov/environment/water/rri_mainriv.htm. Accessed May 2003.

Wilhelms, S. and L. Yates, U.S. Army Corps of Engineers. 1995. *Improvement of Reservoir Releases by Aeration.* http://el.erdc.usace.army.mil/elpubs/pdf/wqtnms01.pdf. Accessed December 2005.

Practices to Restore or Maintain Aquatic and Riparian Habitat

Several options are available for the restoration or maintenance of aquatic and riparian habitat in the area of a reservoir impoundment or in portions of the waterway downstream from a dam. One set of practices is designed to augment existing flows that result from normal operation of the dam. These include operation of the facility to produce flushing flows, minimum flows, or turbine pulsing. Another approach to producing minimum flows is to install small turbines that operate continuously. Installation of reregulation weirs in the waterway downstream from the dam can also achieve minimum flows. Finally, riparian improvements are discussed for their importance and effectiveness in restoring or maintaining aquatic and riparian habitat in portions of the waterway affected by the location and operation of a dam.

A report from the National Academies' National Research Council, released in June 2004, illustrates the importance of maintaining instream flows and critical wildlife habitat in streams where dams are present and notes that areas along Nebraska's Platte River are properly designated as "critical habitats" for the river's endangered whooping crane and threatened piping plover. A series of dams and reservoirs have been constructed in the river basin for flood control and to provide water for farm irrigation, power generation, recreation, and municipal use. The alterations to the river and surrounding land caused by this extensive water-control system, however, resulted in habitat changes that were at odds with the protection of the listed species.

Conflicts over the protection of federally listed species and water management in the Platte River Basin have existed for more than 25 years. In recent years, the Fish and Wildlife Service of the U.S. Department of the Interior issued a series of biological opinions indicating that new water depletions would have to be balanced by mitigation measures, and a lawsuit forced the designation of "critical habitat" for the piping plover. These and other controversies prompted the Department of the Interior and the Governance Committee of the Platte River Endangered Species Partnership to request that the National Research Council examine whether the current designations of "critical habitat" for the whooping crane and piping plover are supported by existing science. The National Research Council was also asked to assess whether current habitat conditions are affecting the survival of listed species or limiting their chances of recovery, and to examine the scientific basis for the department's instream-flow recommendations, habitat-suitability guidelines, and other decisions. The report concludes that in most instances habitat conditions are indeed affecting the likelihood of species survival and recovery.

Case Study: Restoring Flows in Green River, Kentucky

The Green River, located in south central Kentucky, is one of the most diverse rivers in the United States in terms of aquatic life. Its watershed supports 151 species of fishes, 59 species of freshwater mussels, and a vast collection of cave flora and fauna. More than one third of the fish species in the Green Rover are considered rare, threatened, or endangered at the state or federal level. Fourteen mussel species have disappeared from the river in the past few decades. The U.S. Army Corps of Engineers and the Nature Conservancy believe loss of some of these species may be due to hydrologic modifications from the Green River Dam.

The dam was built by the U.S. Army Corps of Engineers in 1969 to control floods and provide for recreational uses. It completely stops the flow of the river, and dam operators release water through a concrete pipe, giving them complete control of the river's flow. For most of the year the release of water resembles natural flows, but during certain times of year flow is altered to prevent flooding and to allow for fishing and recreational boating. Prolonged out-of-season high flows could be harmful to fish spawning and mussel reproduction.

In 1999 the Nature Conservancy and the U.S. Army Corps of Engineers began working together to make the flow of the Green River more closely resemble natural conditions. The difference in reservoir levels in the summer and winter was reduced (i.e. reservoir levels were made more similar during these months). This allowed for less water to be released in the autumn, resulting in more even flows year round. Changes to reservoir management levels reduced the out-of-season high flow period, which helped to improve the ecological health of the river. In 2002 the Corps began to implement this new plan.

Source:

Postel, S. and B. Richter. 2003. Green River, Kentucky. From *Rivers for Life: Managing Water People and Nature*. Island Press, Washington, D.C. and Covelo, California.

Flow Augmentation

Operational procedures such as flow regulation, flood releases, or fluctuating flow releases all have the potential for detrimental impacts on downstream aquatic and riparian habitat. When evaluating solutions associated with degraded aquatic and riparian habitat, stakeholders must balance operational procedures to address the needs of downstream aquatic and riparian habitat with the requirements of dam operation. There are often legal and jurisdictional requirements for an operational procedure at a particular dam that should also be considered (USDOI, 1988).

A flushing flow is a high-magnitude, short-duration release for the purpose of maintaining channel capacity and the quality of instream habitat by scouring the accumulation of fine-grained sediments from the streambed. For example, at Owens River in the Eastern Sierra Nevada Mountains, California, a study found that wild salmonids prefer to deposit their eggs in streambed gravel that is free of fine sediments (Kondolf et al., 1987). Availability of suitable instream habitat is a key factor limiting spawning success. Flushing flows wash away the sediments without removing the gravel. Flushing flows also prevent the encroachment of riparian vegetation. According to a study of the Trinity River Drainage Basin in northwestern California (Nelson et al., 1987), remedial and maintenance flushing flows suppress riparian vegetation and maintain the stream channel dimensions necessary to provide instream habitat in addition to preventing large accumulations of sediment in river deltas. Recommendations for the use of flushing flows as part of an overall instream management program are becoming more common in areas downstream of water development projects in the western United States. For instance, Wesche and others (1987) used a sediment transport input-output model to determine the required flushing flows for removing fine-grained sediments from portions of the Little Snake River that served as instream habitat for Colorado cutthroat trout (*Oncorhynchus clarki*). The flushing flows reduced the overall mass of sediment covering the channel bottom and removed the finer grained material, thereby increasing the size of the residual sediment forming the bottom streambed deposits. This larger-sized residual sediment was more suited as instream habitat for the trout.

However, it is important to keep in mind that flushing flows are not recommended in all cases. Flushing flows of a large magnitude may cause flooding in the old floodplain or depletion of gravel below a dam. Flushing flows are more efficient and predictable for small, shallow, high-velocity mountain streams unaltered by dams, diversions, or intensive land use. Routine maintenance generally requires a combination of practices including high flows coupled with sediment dams or channel dredging, rather than simply relying on flushing or scouring flows (Nelson et al., 1988).

The water quality and quantity in larger mainstem rivers is largely determined by what they receive from their many smaller tributaries. Many of the degrading impacts of developments encroaching on riparian areas along these tributaries are carried downstream and are often amplified once they drain into the larger mainstem rivers. On the other hand, tributaries with relatively undisturbed riparian vegetation contribute steady amounts of clean, cool water to the mainstems and provide organic matter needed by aquatic organisms downstream (Cohen, 1997).

Most of the annual flow in the smaller headwater streams is provided by groundwater that, in turn, is replenished by rainwater falling onto and infiltrating the soil under vegetated areas. Since water seeps slowly through the soil, the surface water flowing in streams can represent rainwater that fell days, weeks or even months ago. This regular, continuous seepage of groundwater that keeps streams flowing is called "baseflow." Baseflow is critical to stream life and water quality. Low flow periods are typically the most stressful periods for aquatic organisms, resulting in crowding due to less available habitat, elevated water temperatures in the summer and greater freezing in the winter. Sportfish, fish food animals, and water plants require a stable, continuous flow of water, particularly during dry periods (Cohen, 1997).

Groundwater discharge is a major source of streamflow for smaller streams, especially during hot and dry summers, where the discharge both augments the streamflow and mitigates harmful temperature increases. This groundwater discharge is key to maintaining adequate water levels and temperatures in streams to support aquatic life. Small streams deprived of groundwater flow may even dry up completely, a condition that obviously limits their value for aquatic life and water supplies (Cohen, 1997). Achieving a balance among many uses, such as water supply and fishery, is very important.

In the design, construction, and operation of dams, the minimum flow requirements to support aquatic organisms and other water-dependent wildlife in downstream areas that are affected by changes in baseflow due to the presence of the dam should be addressed. Minimum flow requirements are typically determined to protect or enhance one or a few critical species of fish. Other fish, aquatic organisms, and riparian wildlife are usually assumed to be protected by these flows. For instance, when minimum flows at the Conowingo Dam (Susquehanna River, Maryland-Pennsylvania border) were increased from essentially zero to 5,000 cfs, up to a 100-fold increase was noted in the abundance of macroinvertebrates downstream from the dam (USDOE, 1991). When minimum flows were increased from 1.0 cfs to 5.5 cfs at the Rob Roy Dam (Douglas Creek, Wyoming), there was a four- to six-fold increase in the number of brown trout (*Salmo trutta*) found at downstream locations (USDOE, 1991).

Flows at Rush Creek on the Eastern slope of the Sierra Nevada Mountains in California have averaged about 50 percent of their pre-diversion levels (Stromberg and Patten, 1990). Since the construction of the Grant Lake Reservoir, the influence of flow rates and volumes on the growth of riparian trees has been studied. Stromberg and Patten (1990) found that a strong relationship exists between growth rates of riparian tree species and annual and prior-year flow volumes. Once the level of growth needed to maintain populations is known, the relationship between growth and flow can be used to determine the instream flow needs of riparian vegetation. Instream models for Rush Creek suggest that flow requirements of riparian vegetation may be greater than requirements for fisheries.

Seasonal discharge limits can be established to prevent excessive, damaging rates of flow release. Limits can also be placed on the rate of change of flow and on the stage of the river (as measured at a point downstream of the dam facility) to further protect against damage to instream and riparian habitat. Flushing and scouring flows may also be necessary to clean some streambeds and to provide the proper substrate for aquatic species.

Several options exist for creating minimum flows in the tailwaters below dams. As indicated in the case studies described below, the selection of any particular technique as the most cost-effective is site-specific and depends on several factors including adequate performance to achieve the desired instream and riparian habitat characteristic, compatibility with other requirements for operation of the hydropower facility, availability of materials, and cost.

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. At some facilities, this practice may dictate that modifications be made to the existing sluice outlets to maintain continuous low releases. Continuous low-level sluice releases at Eufala Lake and Fort Gibson Lake (Oklahoma) provided minimum flows needed to sustain downstream fish populations. The sluicing also had the benefit of improving DO levels in tailwaters downstream of these two dams such that fish mortalities, which had been experienced in the tailwaters below these two dams prior to initiating this practice, no longer occurred (USDOE, 1991).

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.

A study undertaken at the Douglas Dam (French Broad River, Tennessee) suggests some of the site-specific factors that should be considered when evaluating the advantages of practices such as turbine pulsing, sluicing, or other alternatives for providing minimum flows and improving DO levels in reservoir releases. Two options for maintaining minimum flows (turbine pulsing and sluicing), and two aeration alternatives (operation of surface water pumps and diffusers) were evaluated for their effectiveness, advantages, and disadvantages in providing minimum flows and aeration of reservoir releases. Computer modeling indicated that either turbine pulsing or sluicing could improve DO concentrations in releases by levels ranging from 0.7 to 1.5 mg/L. This is slightly below the level of improvement that might be expected from operation of a diffuser system for aeration. A trade-off can also be expected at this facility between water saved by frequent short-release pulses and the higher maintenance costs due to operating turbines on and off frequently (Hauser et al., 1989). Hauser et al. (1989) found that schemes of turbine pulsing ranging from 15-minute intervals to 60-minute intervals every 2 to 6 hours were found to provide fairly stable flow regimes after the first 3 to 8 miles downstream at several TVA projects. However, at points farther downstream, less overall flow would be produced by sluicing than by pulsing. Turbine pulsing may also cause waters to rise rapidly, which could endanger people wading or swimming in the tailwaters downstream of the dam (TVA, 1990).

A reregulation weir is one alternative that has been used to establish minimum flows for preservation of instream habitat. This device is installed in the streambed a short distance below a dam and captures hydropower releases. Flows through the weir can be regulated to produce the desired conditions of water level and flow velocities that are best for instream habitat. As discussed previously in this chapter, reregulation weirs can also be used in some circumstances to improve levels of dissolved oxygen in reservoir releases.

The installation of such an instream structure requires some degree of planning and design since the performance of the weir will affect both the downstream water surface elevation and the

Case Study: Reregulation Weir Found Cost-Effective

Completion of the South Holston Dam in 1950 radically changed the South Fork Holston River in Tennessee, creating the South Holston Reservoir and a 20-mile stretch of water below it where temperatures had dropped enough to support cold-water fish species. Since its installation, the hydropower activities of the dam resulted in drastically fluctuating water levels that wreaked havoc with the riverbed and low DO levels that limited the river's productivity.

In 1991 the TVA constructed a 7.5 foot-tall aerating labyrinth weir below the dam. The weir serves to maintain a minimum flow of 90 cfs downstream of the dam. During periods when the turbines are not operating, valved pipes located near the bottom of the weir allow controlled drainage of the weir pool. Trout Unlimited purchased and donated to the TVA valves for the weir that maximize releases by increasing minimum flows from the weir pool. By raising these minimum flows, the valves expand wetted areas in the tailwater, stabilizing and increasing the amount of trout and insect habitat. When no hydro-generation is scheduled, TVA releases water through the turbines twice a day to refill the weir pool. This helps to prevent riverbed dry-out and provides additional habitat for fish and other aquatic life.

Three alternatives were assessed for their effects on river hydraulics and on operation of the hydropower facility. These include a reregulation weir, turbine pulsing, and installation of a small generating unit in the existing tailrace that would operate at all times when the existing unit was not operating. A reregulation weir, such as the labyrinth weir, was found to be the most cost-effective alternative for providing a minimum flow below the South Holston Dam for maintenance of instream trout habitat.

The weir also functions as an artificial waterfall to increase DO in the water. As the water passes over the weir, approximately 40-50% of the oxygen deficit is recovered. In addition, water from the dam is aerated via turbine venting, a process where air flow is introduced into low-pressure zones just below the turbines to create small air bubbles. Oxygen from the bubbles is absorbed into the oxygen-poor water as it passes through the turbines. The weir and the turbine improvements combine to help maintain the target DO concentration of 6 ppm.

Sources:

Adams, J.S., and G.E. Hauser. 1990. *Comparison of Minimum Flow Alternatives South Fork Holston River Below South Holston Dam*. Tennessee Valley Authority, Engineering Laboratory, Norris, TN. Report No. WR28-1-21-102.

Tennessee Wildlife Resources Agency. 2003. *Tailwater trout population monitoring*. http://www.homestead.com/twra4streams/abstract4.html. Accessed August 2003.

Tennesse Valley Authority. No Date. *Water Quality Improvements at Tributary Dams, South Holston Dam*. http://www.tva.gov/environment/water/rri_triblist.htm#south_holston. Accessed August 2003.

Trout Unlimited. 2002. *South Holston River*. http://www.tutv.org/2002_shows/south_holston_river.html. Accessed August 2003. [Link not active]

velocity of the discharge. These relationships have been investigated for the Buford Dam (Chattahoochee River, Georgia), where computer simulations of a proposed reregulation weir indicated that a discharge of 500 cfs created the best instream habitat conditions for juvenile brown trout (*Salmo trutta*). Instream habitat for adult brook trout (*Salvelinus fontinalis*), adult brown trout, and adult rainbow trout (*Oncorhynchus mykiss*) was most desirable at discharges in the vicinity of 1,000 to 2,000 cfs (Nestler et al., 1986a).

Small turbines are another alternative that has been evaluated for establishing minimum flows. Small turbines are capable of providing continuous generation of power using small flows, as opposed to operating large turbine units with the resultant high flows. In a study of alternatives for providing minimum flows at the Tims Ford Dam (Elk River, Tennessee), small turbines were found to represent the most attractive alternative from a cost-benefit perspective. The other alternatives evaluated included continuous operation of a sluice gate at the dam, pulsing of the existing turbines, and construction of an instream rock gabion regulating weir downstream of the dam (TVA, 1985).

Riparian Improvements

Riparian improvements are another strategy that can be used to restore or maintain aquatic and riparian habitat around reservoir impoundments or along the waterways downstream from dams. In fact, Johnson and LaBounty (1988) found that riparian improvements were more effective, in some cases, than flow augmentation for protection of instream habitat. In the Salmon River (Idaho), a variety of instream and riparian habitat improvements have been recommended to improve the indigenous stocks of Chinook salmon (*Oncorhynchus tshawytscha*). These improvements include reducing sediment loading in the watershed, improving riparian vegetation, eliminating barriers to fish migration (see sections discussing this practice below), and providing greater instream and riparian habitat diversity (Andrews, 1988).

Maintaining and improving riparian areas upstream of a dam may also be an important consideration for reducing flow-related impacts to dams. Riparian areas along brooks and smaller streams are sometimes altered in a manner that impairs their ability to detain and absorb floodwater and stormwater (e.g., removal of forest cover or increased imperviousness). The cumulative impact of the riparian changes results in the smaller streams discharging increased volumes and velocities of water, which then result in more severe downstream flooding and increased storm damage and/or maintenance to existing structures (such as dams). These downstream impacts may occur even though main stem floodplains and riparian areas are safeguarded and remain close to their natural condition (Cohen, 1997).

Practices to Maintain Fish Passage

Migrating fish populations may be unable to travel up or downstream because of the presence of a dam or suffer losses when passing through the turbines of hydroelectric dams unless these facilities have been equipped with special design features to accommodate fish passage. The effect of dams and hydraulic structures on migrating fish has been studied since the early 1950s in an effort to develop systems or identify operating conditions that would minimize mortality rates. Selecting a device or management strategy for optimal fish passage in a stream or river with a dam requires careful analysis of a variety of factors, such as species, type and operational strategy of the dam, and the physical characteristics of the river system.

Devices such as fish ladders and bypass channels can help fish travel past dams, but typically result in increased mortality due to the hardship and stress involved with passing through these structures. In addition, the fish passage structures have to be placed in a suitable entrance location, have a flow that is attractive to the species of concern, be continually maintained, and possess the hydraulic conditions necessary for the target species (Larinier, 2000). With all of these requirements, the success of a fish ladder or similar device is often uncertain. Passage through the hydraulic turbines of a hydropower dam can cause increased stress as a result of changes in velocity or pressure and the possibility of electric shocks from the turbines and can lead to increased mortality (Larinier, 2000).

The safe passage of fish either upstream or downstream through a dam requires a balance between operation of the facility for its intended uses and implementation of practices that will ensure safe passage of fish. The United States Congress' Office of Technology Assessment (OTA) report on fish passage technologies at hydropower facilities provides an excellent overview of fish passage technologies and discusses some of the economic considerations associated with the safe passage of fish (OTA, 1995).

Case Study: The White Salmon's Condit Dam

Condit Dam is located on the National Wild and Scenic White Salmon River in Washington State. The operating license for the dam expired in 1993 and FERC had to decide whether and under what conditions to issue a new license for the dam. Fish passage and dam removal were considered as alternatives because 1) the dam produces little electricity and blocks anadromous fish passage to the entire river and 2) the Northwest Power Planning Council's Fish and Wildlife Program called for FERC to require the best biological means of allowing salmon and steelhead to access their historical spawning and rearing habitat in the White Salmon River. In 1997, after five years of research and work, FERC began to require fish passage and other measures for Condit Dam.

Due to the high cost of implementing a new fish passage system, the owners of the dam, PacifiCorps, asked for assistance from American Rivers and the Yakima Indian Nation to investigate removing the dam. American Rivers, in conjunction with the Yakima Indian Nation and FERC researched the costs of removing Condit Dam. Although estimates varied, PacifiCorps decided it was more affordable to remove the dam than to construct fish passage facilities. An agreement was reached in September 1999 where the dam would operate for seven more years, without the costly FERC mandated requirements, in order to offset removal and mitigation costs. Funds generated during this period go toward the dam removal project. The overall costs related to the dam are estimated at a maximum of $17.15 million, including $13.65 million for removal costs, $2 million for permitting and mitigation costs, $1 million toward a fund to be administered by the Yakama Nation for enhancement of the White Salmon River fishery, and $500,000 for enhancement of a traditional Indian fishing site at the mouth of the White Salmon River. Removal of the dam is scheduled to begin in October 2006, although as of 2002, the Washington Department of Ecology had not finalized the Environmental Impact Statement required before dam removal. The Washington Department of Fish and Wildlife estimates that the removal could reestablish runs of about 700 steelhead adults (*Oncorhynchus mykiss*), 4,000 spring chinook adults (*Oncorhynchus tshawytscha*), 1,100 fall chinook, and 2,000 coho salmon (*Oncorhynchus kisutch*).

Sources:

American Rivers. 1997. *Threat: "Deadbeat" Hydropower Dam* http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1269. Accessed August 2003.

American Rivers. No Date. *Benefits of Condit Dam Removal.* http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=441. Accessed August 2003.

American Whitewater.1999. *Condit Dam (White Salmon River WA) Removal Agreement.* http://www.americanwhitewater.org/archive/article/4. Accessed August 2003.

Grimaldi, J.V. 1999, September 22. Deal struck to remove dam in state—White Salmon River will be cleared for fish in 2006. *The Seattle Times.*

Robinson, E. 2002, June 10. PacifiCorp seeks delay in removal of dam. *The Columbian.*

U.S. Department of Interior. 1999. *PacifiCorp, American Rivers, Yakama Nation Historic Condit Dam removal agreement to be signed*. http://www.doi.gov/news/archives/pacifi.html. Accessed August 2003.

The U.S. Fish and Wildlife Service and its partners have created a database that makes information about barriers to fish passage in the United States available to policy makers and the public. The database, known as the Fish Passage Decision Support System (FPDSS), is part of the U.S. Fish and Wildlife's National Fish Passage Program and is available at https://ecos.fws.gov/fpdss/index.do. Information about National Fish Passage Program is available at http://fisheries.fws.gov/fwsma/fishpassage.

Available fish-protection systems for hydropower facilities fall into one of four categories based on their mode of action (Stone and Webster, 1986): behavioral barriers, physical barriers, collection systems, and diversion systems. These are discussed in separate sections below, along with additional practices that have been successfully used to maintain fish passage: spill and water budgets, fish ladders, fish lifts, advanced hydroelectric turbines, transference of fish runs, and constructed spawning beds.

Upstream fish passage systems have been constructed at approximately 10 percent of the FERC licensed hydropower plants. Upstream fish passage systems such as fish ladders and lifts are considered adequately developed for anadromous such as salmon, American shad (*Alosa sapidissima*), alewives (*Alosa pseudoharengus*), and blueback herring (*Alosa aestivalis*). Fish passage systems for riverine fish have not been specifically designed, although some of these species will use fish passage systems designed for anadromous species (OTA, 1995).

Behavioral Barriers

Behavioral barriers use fish responses to external stimuli to keep fish away from the intakes or to attract them to a bypass. Since fish behavior is notably variable both within and between species, behavioral barriers cannot be expected to prevent all fish from entering hydropower intakes. Environmental conditions such as high turbidity levels can obscure some behavioral barriers, such as lighting systems and curtains. Competing behaviors such as feeding or predator avoidance can also be a factor influencing the effectiveness of behavioral barriers at a particular time.

Electric screens, bubble and chain curtains, light, sound, and water jets have been evaluated in laboratory or field studies, and show mixed results. Despite numerous studies involving existing devices and new technologies, very few permanent applications of behavioral barriers have been realized (EPRI, 1999). Some authors suggest using behavioral barriers in combination with physical barriers (Mueller et al., 1999).

Electrical screens are intended to produce an avoidance response in fish. This type of fish-protection system is designed to keep fish away from structures or to guide them into bypass areas for removal. Fish seem to respond to the electrical stimulus best when water velocities are low. Tests of an electrical guidance system at the Chandler Canal diversion (Yakima River, Washington) showed the efficiency ranged from 70 to 84 percent for velocities of less than 1 ft/sec. Efficiencies decreased to less than 50 percent when water velocities were higher than 2 ft/sec (Pugh et al., 1971). The success of electrical screens may also be species-specific and size-specific. An electrical field strength suitable to deter small fish may result in injury or death to large fish, since total fish body voltage is directly proportional to fish body length (Stone and Webster, 1986). Electrical screens require constant maintenance of the electrodes and the associated underwater hardware to maintain effectiveness. Surface water quality, in particular, can affect the life and performance of the electrodes.

Air bubble curtains are created by pumping air through a diffuser to create a continuous, dense curtain of bubbles, which can cause an avoidance response in fish. Many factors affect the response of fish to air bubble curtains, including temperature, turbidity, light intensity, water velocity, and orientation in the channel. Bubbler systems should be constructed from materials that are resistant to corrosion. Bubbler systems should be installed with adequate positioning of the diffuser away from areas where siltation could clog the air ducts.

Hanging chains are used to provide a physical, visible obstacle that fish will avoid. Hanging chains are both species-specific and lifestage-specific. Their efficiency is affected by such variables as instream flow velocity, turbidity, and illumination levels. Debris can limit the performance of hanging chains; in particular, buildup of debris can deflect the chains into a nonuniform pattern and disrupt hydraulic flow patterns.

Strobe lights repel fish by producing an avoidance response. A strobe light system at Saunders Generating Station in Ontario was found to be 67 to 92 percent effective at repelling or diverting eels (EPRI, 1999). Turbidity levels in the water can affect strobe light efficiency. The intensity and duration of the flash can also affect the response of the fish; for instance, an increase in flash duration has been associated with less avoidance. Strobe lights also have the potential for far-field fish attraction, since they can appear to fish as a constant light source due to light attenuation over a long distance (Stone and Webster, 1986). Strobe lights at Hiram M Chittenden Locks in Seattle, Washington were examined to determine how fish respond, depending on strobe light distance. Vertical avoidance was 90 to 100 percent when the lights were 0.5 m away, 45 percent when the lights were 2.5 m away, and 19 percent if the lights were 4.5 to 6.5 m away (EPRI, 1999).

Mercury lights have been successfully used to attract fish to passage systems and repel them from dangers around dams. Studies of mercury lights suggest their effectiveness is species-specific; alewives (*Alosa pseudoharengus*) were attracted to a zone of filtered mercury light, whereas coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*Oncorhynchus mykiss*) displayed no attraction to mercury light (Stone and Webster, 1986). In another field test conducted on the Susquehanna River, mercury lights proved extremely effective in attracting gizzard shad (OTA, 1995). Although the results have been mixed, the low overall cost of mercury light systems has led to continued research on their effectiveness (Duke Engineering & Services, Inc., 2000).

Underwater sound, broadcast at different frequencies and amplitudes, has also been shown to be effective in attracting fish away from dams or repelling fish from dangers around dams, although the results of field tests are not consistent. Fish have been attracted, repelled, or guided by the sound. A study prepared for the U.S. Department of Energy showed that low-frequency, high particle motion was effective at invoking flight and avoidance responses in salmonids (Mueller et al., 1998). These finding agree with Knudsen et al. (1994), who found that low frequencies are efficient for evoking awareness reactions and avoidance responses in juvenile Atlantic salmon.

Not all fish possess the ability to perceive sound or localized acoustical sources (Harris and Van Bergeijk, 1962). Fish also frequently seem to become habituated to the sound source.

Poppers are pneumatic sound generators that create a high-energy acoustic output to repel fish. Poppers have been shown to be effective in repelling warm-water fish from water intakes. Laboratory and field studies conducted in California indicate good avoidance for several freshwater species such as alewives (*Alosa pseudoharengus*), perch, and smelt, but salmonids do not seem to be effectively repelled by this device (Stone and Webster, 1986). One important maintenance consideration is that internal “O” rings positioned between the air chambers have been found to wear out quickly. Other operation and maintenance considerations are air entrainment in water inlets and vibration of structures associated with the inlets.

Water jet curtains can be used to create hydraulic conditions that will repel fish. Effectiveness is influenced by the angle at which the water is jetted. Although effectiveness averages 75 percent in repelling fish (Stone and Webster, 1986), not enough is known to determine what variables affect the performance of water jet curtains. Important operation and maintenance concerns would be clogging of the jet nozzles by debris or rust and the acceptable range of stream flow conditions, which contribute to effective results.

Hybrid barriers, or combinations of different barriers, can enhance the effectiveness of individual behavioral barriers. A chain net barrier combined with strobe lights has been shown in laboratory studies to be up to 90 percent effective at repelling some species and sizes of fish. Combinations of rope-net and chain-rope barriers have also been tested with good results. Barriers with horizontal components in the water column, as well as vertical components, are more effective than those with vertical components alone. Barriers having elements with a large diameter are more effective than those with a small diameter, and thicker barriers are more effective than thinner barriers. Therefore, diameter and spacing of the barriers are factors influencing performance (Stone and Webster, 1986). With hanging chains, illumination appears to be a necessary factor to ensure effectiveness. Their effectiveness was increased with the use of strobe lights (Stone and Webster, 1986). Effectiveness also increased when strobe lights were added to air bubble curtains and poppers (Stone and Webster, 1986).

Physical Barriers

Physical barriers are diversion systems that lead or force fish to bypasses that transport them above or below the dam (FAO, 2001). Physical diversion structures deployed at dams include angled screens, drum screens, inclined plane screens, louvers, and traveling screens. The success and effectiveness of physical barriers has been found to be specific to individual hydropower facilities. Thus, a sufficient range of performance data is not available for categorizing the efficiency of specific designs in a particular set of site conditions and fish population assemblages (Mattice, 1990).

Angled screens are used to guide fish to a bypass by guiding them through the channel at some angle to the flow. Coarse-mesh angled screens have been shown to be highly effective with numerous warm- and cold-water species at adult life stages. Fine-mesh angled screens have been shown in laboratory studies to be highly effective in diverting larval and juvenile fish to a bypass with resultant high survival. Performance of angled screens can vary by species, stream velocity, fish length, screen mesh size, screen type, and temperature (Stone and Webster, 1986). Clogging from debris and fouling organisms is a maintenance problem associated with angled screens.

Angled rotary drum screens oriented perpendicular to the flow direction have been used extensively to lead fish to a bypass. Angled rotary drum screens tend not to experience the major operational and maintenance clogging problems of stationary screens, such as angled vertical screens. Maintenance of angled rotary drum screens typically consists of routine inspection, cleaning, lubrication, and periodic replacement of the screen mesh (Stone and Webster, 1986).

An inclined plane screen is used to divert fish upward in the water column into a bypass. Once concentrated, the fish are transported to a release point below the dam. An inclined plane pressure screen at the T.W. Sullivan Hydroelectric Project (Willamette Falls, Oregon) is located in the penstock of one unit. The design is effective in diverting fish, with a high survival rate. However, this device has been linked to injuries in some species of migrating fish, and it has not been accepted for routine use (Stone and Webster, 1986).

Louvers consist of an array of evenly spaced, vertical slats aligned across a channel at an angle leading to a bypass. The turbulence they create is sensed and avoided by the fish (Stone and Webster, 1986). Louver systems rely on a fish's instincts to use senses other than sight to move around obstacles. Once the louver is sensed, the fish tend to reverse their head first downstream orientation (to head upstream, tail to the louver) and move laterally along it until they reach the bypass (OTA, 1995).

Submerged traveling screens are used to divert downstream migrating fish out of turbine intakes to adjoining gatewell structures, where the fish are concentrated for release downstream. This device has been tested extensively at hydropower facilities on the Snake and Columbia Rivers. Because of their complexity, submerged traveling screens must be continually maintained. The screens must be serviced seasonally, depending on the debris load, and trash racks and bypass orifices must be kept free of debris (Stone and Webster, 1986).

Physical barrier fish diversion systems have been found to work best when specifically designed to the structure and fish being passed. Small differences in design, such as the spacing or depth of the louvers, can mean the difference in success and failure. A successful louver system has been installed at the Holyoke Hydroelectric Power Station, on the Connecticut River. This partial depth louver system was installed in the intake channel at the power plant and successfully passed 86% of the juvenile clupeids and 97% of the Atlantic salmon (*Salmo salar*) smolts (Marmulla, 2001). Another partial depth louver system on the same river has experienced less successful results. The system installed at the Vernon Dam on the Connecticut River is successfully passing about 50% of the Atlantic salmon smolts (OTA, 1995).

Collections Systems

Collection systems involve capture of fish by screening and/or netting followed by transport by truck or barge to a downstream location. Since the late 1970s, the USACE has successfully implemented a program that takes juvenile salmon from the uppermost dams in the Columbia River system (Pacific Northwest) and transports them by barge or truck to below the last dam. The program improves the travel time of fish through the river system, reduces most of the exposure to reservoir predators, and eliminates the mortality associated with passing through a series of turbines (van der Borg and Ferguson, 1989). Survivability rates for the collected fish are in excess of 95 percent, as opposed to survival rates of about 60 percent had the fish remained in the river system and passed through the dams (Dodge, 1989). However, the collection efficiency can range from 70 percent to as low as 30 percent. At the McNary Dam on the Columbia River, spill budgets are also implemented to improve overall passage (discussed in greater detail below) when the collection rate achieves less than 70 percent efficiency (Dodge, 1989).

Spill and Water Budgets

Although often used together, spill and water budgets are independent methods of facilitating downstream fish migration.

Spill budgets provide alternative methods for fish passage that are less dangerous than passage through turbines. Spillways are used to allow fish to leave the reservoir by passing over the dam rather than through the turbines. The spillways must be designed to ensure that hydraulic conditions do not induce injury to the passing fish from scraping and abrasion, turbulence, rapid pressure changes, or supersaturation of dissolved gases in water passing through plunge pools (Stone and Webster, 1986).

In the Columbia River basin (Pacific Northwest), the USACE provides spill on a limited basis to pass fish around specific dams to improve survival rates. At key dams, spill is used in special operations to protect hatchery releases or provide better passage conditions until bypass systems are fully developed or, in some cases, improved (van der Borg and Ferguson, 1989). The cost of this alternative depends on the volume of water that is lost for power production (Mattice, 1990). Analyses of this practice, using a USACE model called FISHPASS, historically has shown that the application of spill budgets in the Columbia River basin is consistently the most costly and least efficient method of improving overall downstream migration efficiency (Dodge, 1989).

In 1995 the National Marine Fisheries Service released a draft biological opinion to save Columbia River Basin Salmon. The opinion was issued after concluding that the current operations of the hydropower system were jeopardizing the Columbia Basin salmon. The opinion addresses safer passage for young fish through the dams and modification to a number of hydropower operations and facilities. It calls for using as much water as possible during fish-passage season to improve flow for fish moving through the system. Specifically the draft called for spilling water over the dams to increase passage of juvenile salmon via non-turbine routes to at least 80 percent. The USACE now runs the Juvenile Fish Transportation Program in cooperation with National Marine Fisheries Service (NOAA, 1995; USACE, 2002b).

The water budget is the mechanism for increasing flows through dams during the out-migration of anadromous fish species. It is employed to speed smolt migration through reservoirs and dams. Water that would normally be released from the impoundment during the winter period to generate power is instead released in the May-June period, when it can be sold only as secondary energy. This concept has been put into practice in some regions of the United States, although quantification of the overall benefits is lacking (Dodge, 1989).

The volume of a typical water budget is generally not adequate to sustain minimum desirable flows for fish passage during the entire migration period. The Columbia Basin Fish and Wildlife Authority has proposed replacement of the water budget on the Columbia River system with a minimum flow requirement to prevent problems of inadequate water volume in discharge during low-flow years (Muckleston, 1990).

Fish Ladders

Fish ladders are the most commonly used structure to enable the safe upstream and downstream passage of mature fish (see Figure 2.9). There are four basic designs: pool-weir, Denil, vertical slot, and steeppass.

Figure 2.9 Fish Ladder at Feather River Hatchery, Oroville Dam, CA (Feather River, n.d.)

Pool-weir fish ladders are one of the oldest and most commonly designed fish passage structures. This design of pool-weir fish ladder consists of stepped pools and weirs that allow fish to pass from pool to pool over the weirs that separate each of them. Pool weir fish ladders are normally used on slopes of about 10-degrees. Some pool weir fish ladders can be modified to increase the number of fish possible that are passed by including submerged orifices that allow fish to pass the fish ladder without cresting the weirs.

Pool-weir fish ladders will pass many different species of fish if they are designed correctly for the environment in which they are employed. OTA (1995) provides details on design and operation of various forms of fish ladders, which is summarized below. Extensive research has been done related to the ability of fish to navigate fish ladders. For example, most salmonids can pass weirs with a fall of approximately one foot. Riverine species such as American shad (*Alosa sapidissima*) will readily pass weirs with a fall of approximately three-quarters of a foot. Regardless of the species passed, most pool-weir fish ladders require additional attraction or auxiliary flow to lead the fish into the ladder (OTA, 1995).

Denil fish ladders are elongated rectangular channels that use internal baffles to dissipate flow energy and allow fish passage. They are widely used in the eastern United States due to their ability to pass a wide range of species from salmonids to riverine species over a wider range of flows than pool-wier ladders. Denil ladders can be employed on slopes from 10 to 25 degrees although 10 to 15 degrees is optimal. Most Denil fish ladders are two to four feet wide and four to eight feet deep. This fish ladder design allows fish to pass at a preferred depth instead of through a jumping action.

Denil ladders do not have resting areas and therefore fish must either be able to pass the ladder in one burst or resting pools must be provided between sections. Resting pools should be provided every 16 to 50 feet depending upon the species being passed. The high flow rates and turbulence associated with Denil fish ladders reduces the demand for attraction flow, which is commonly added to insure good attraction over varying flow rates.

Vertical slot fish ladders are also elongated rectangular channels that use regularly spaced baffles to create steps and resting pools. The vertically oriented slots in the baffles allow fish to pass through the ladder at a preferred depth. Unlike Denil fishways, vertical slot fishways provide a resting area behind each baffle allowing fish to pass in a “burst-rest” manner instead of one sustained motion. The channel created by the baffles is off-center making the baffles on one side of the ladder wider than the opposing side. Eddies that form behind longer baffles allow fish to rest and end the need for resting areas.

Although vertical slot ladders are usually operated at slopes of about 10 degrees, they can be operated over a larger variety of flows. The vertical slots create a water jet that is regulated by the pool on the downstream side of it. This creates a uniform, level flow throughout the ladder.

The steeppass fish ladder, often referred to as the “Alaska steeppass” is a modified Denil fish ladder that is most commonly used in remote areas for the passage of salmonids. Steeppass fish ladders are usually constructed of lightweight materials such as aluminum and can operate on slopes up to 33 %. The construction materials and design allow this type of fish ladder to be deployed as a single unit to remote areas. The baffles used in steeppass ladders are more aggressively designed, which allow the ladder to more effectively control water flow.

The steeppass ladder is not without its limitations. Due to their narrow design, steeppass ladders are more susceptible to clogging due to debris and changes in flow upstream or downstream of the ladder.

Although fish ladders can be extremely efficient at passing fish, small changes in design can greatly improve their functionality. A good example of this is the John Day Dam located on the Columbia River. The original design focused on the passage of salmonids and therefore only passed about 17% of the American shad (*Alosa sapidissima*) using the ladder. Research indicated that simple design changes could allow for the passage of riverine species such as American shad. By changing the placement of the weirs within the fish ladder, the fish ladder was able to pass 94% of the salmonids and American shad passage increased to 74% (Monk et al., 1989).

According to the U.S. Army Corps of Engineers, Portland District (1997), the success rate for adults negotiating the fish ladders at dams in the Columbia River Basin is about 95%. The U.S. Fish and Wildlife Agency designs fishways assuming a 90% efficiency rate. Although there are few studies documenting actual efficiency of fish ladders, it is recognized that not all fishways are equally effective (for various reasons, such as predation, problems associated with gas supersaturation, and physical damage to the passing fish). Some fishways installed in the last 20 years are less effective than newer ones (when federal licenses began to include fish passage requirements). Maine Department of Marine Resources (DMR) estimates efficiency between 75% and 90% (Presumpscot River Plan Steering Committee, 2002).

Case Study: King County, Washington Neighborhood Group Dedicates Fish Ladder

Coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Oncorhynchus clarki*) have access to an extra 1.5 miles of spawning and rearing habitat in Denny Creek (Kirkland, WA) thanks to a cooperative fish ladder project between King County and a Kirkland-area neighborhood group. The project has transformed 230 feet of creek from what had become a stretch of sediment filled waterway under a fish-blocking, eight-foot waterfall. The erosion-caused waterfall was blamed in part on a 70-year-old concrete bridge. The new fish ladder looks like a naturally sloping stream through the woods, traversing pools formed by large boulders, stream cobbles, and large woody debris. The project included the installation of 16 weirs to create step pools for making fish passage possible. Volunteers then planted native trees and shrubs such as cedar, fir, salmonberry, lady ferns and alder, alongside the creek to prevent erosion. The fish ladder was completed in October 2002 over a five week time period, with the native plant salvage and final plantings coordinated by two boy scouts earning their eagle badges.

Denny Creek Neighborhood Alliance members initiated, designed, and provided volunteers to do much of the work on the project. They completed construction documents, biological assessments and obtained funding from county, private, and federal sources. The group received an appropriation of $50,631 sponsored by Council member Hague, $47,330 from the King County Water Works Block Grant Program, $34,900 from the National Fish and Wildlife Foundation, and $12,400 from the USACE. King County Parks resource coordinator Mike Crandell said Parks employees performed construction, using free clay from a landslide to seal the bottom of the creek, and large woody debris from park storm damage. The King County Department of Natural Resources and Parks also provided technical assistance, project management, permits, and volunteer coordination. The county owns and maintains the fish ladder.

“The Denny Creek Fish Passage Project is a good example of what can be accomplished when a community and local government join forces,” said King County Parks Division manager Bob Burns. “This partnership can serve as a model for other local projects.” The project was recognized in 2003, when the National Stone, Sand & Gravel Association gave the King County Department of Natural Resources and Parks and the Denny Creek Neighborhood Alliance a Pantheon “Landscape Use” Award.

Sources:
King County. 2002. *King County, Neighborhood Group to Dedicate Fish Ladder*. http://dnr.metrokc.gov/dnradmin/press/2002/1011grnt.htm. Accessed June 2003.

King County. 2003. *King County, Neighborhood Group Receive National “Landscape” Award for Denny Creek Fish Ladder Project*. http://dnr.metrokc.gov/dnradmin/press/2003/0429award.htm. Accessed August 2003.

Fish Lifts

Fish lifts describe both fish elevators and locks, which are used to capture fish at the downstream side of a structure and then move them above the structure. Like fish ladders, these systems require sufficient attraction flow to move fish into the lift area. Lift systems can be advantageous because they are not species or flow specific. They can also be employed at structures too tall for fish ladders and to pass species with reduced swimming ability.

Lift systems have the potential to move large numbers of fish if they are operated efficiently. These systems can be automated to allow operation much like fish ladders. Fish lift systems do require additional operation and maintenance costs and are subject to mechanical failures not associated with fish ladders.

Most lift systems require either an active or passive bypass system to move fish far enough upstream to avoid entrainment in the flow through the dam. Passive bypass systems may include constructed waterways or pipes that discharge passed fish sufficiently up-steam of the structure. Active bypass systems include trucking and pumping operations that discharge the fish safely upstream of the structure. Active bypass systems, especially pumping systems, have come under scrutiny for fish behavior and health reasons. During the pumping process, fish may be subject to descaling and/or death due to overcrowding. After release, the fish may have orientation problems and therefore be subject to higher rates of predation mortality. Due to these concerns the United States Fish and Wildlife service has generally opposed the use of fish pumps (OTA, 1995).

Case Study: Conowingo Dam

One of the most successful fish lift systems is located at the Conowingo Dam on the Susquehanna River in Maryland. A temporary lift system was installed on the west side in the 1970s, and a permanent lift system was built in 1991. The system was completed in 1991 at a total cost (adjusted to 1990 dollars) of $11.9 million. The lifts consist of two elevators that collect anadromous fish, such as American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*), at the base of the dam and lift them to the top. Between 1985 and 1998, approximately 350,000 adult shad were passed over the Conowingo dam and the annual return of shad increased from 2,000 to over 100,000 annually. The fish lift system has the capacity of lifting 1.5 million shad and 10 million river herring (*Alosa chrysochloris*) per year. Fish counts conducted downstream of the dam have indicated the number of American shad using the lift, peaked in 1997 at 104,000 fish.

Sources:
Maryland Department of Natural Resources. 1999. Anadramous fish restoration on the Susquehanna. PPRP Power Plant Update. Vol. 5, No. 4. Available online at: http://www.esm.versar.com/pprp/updates/sum99/fish/fish.htm. Accessed March 2004.

Nichols, A.B. 1992. *Life System Helps Fish Overcome Dammed Waters*. Water Environment and Technology, 4(9): 40-42. Water Environment Federation, Alexandria, VA

Susquehanna River Anadromous Fish Restoration Cooperative. n.d. *Migratory Fish Restoration and Passage on the Susquehanna River*. Available online at: http://sites.state.pa.us/PA_Exec/Fish_Boat/migfishs.pdf.

Advanced Hydroelectric Turbines

Hydroelectric turbines can be designed to reduce impacts to juvenile fish passing through the turbine as it operates. Most research on advanced hydroelectric turbines is being carried out by power producers in the Columbia River basin (U.S. Army Corps of Engineers and public utility districts) who are looking to improve the survival of hydroelectric turbine-passed juvenile fish by modifying the operation and design of turbines. Development of low impact turbines is also being pursued on a national scale by the U.S. Department of Energy (Cada, 2001).

In the last few years, field studies have shown that improvements in the design of turbines have increased the survival of juvenile fish. 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. Overall, improvements in turbine design and operation, and new field, laboratory, and modeling techniques to assess turbine-passage survival, are contributing towards improving downstream fish passage at hydroelectric power plants (Cada, 2001).

The redesign of conventional turbines for fish passage has focused on strategies to reduce obstructions and to narrow the gaps between moveable elements of the turbine that are thought to injure fish. The effects of changes in the number, size, orientation, or shape of the blades that make up the runner (the rotating element of a turbine which converts hydraulic energy into mechanical energy) are being investigated (Cada, 2001).

The USACE has put considerable resources into improving turbine passage survival. The USACE Turbine Passage Survival Program (TSP) was developed to investigate means to improve the survival of juvenile salmon as they pass through turbines located at Columbia and Snake River dams. The TSP is organized along three functional elements that are integrated to achieve the objectives (Cada, 2001):

- Biological studies of turbine passage at field sites
- Hydraulic model investigations
- Engineering studies of the biological studies, hydraulic components, and optimization of turbine operations

Additional information about USACE efforts with advanced hydroelectric turbines is available at http://hydropower.inel.gov/turbines/pdfs/amfishsoc-fall2001.pdf.

The U.S. Department of Energy (DOE) supports development of low impact turbines under the Advanced Hydropower Turbine System (AHTS) Program. The AHTS program explores innovative concepts for turbine design that will have environmental benefits and maintain efficient electrical generation. The AHTS program awarded contracts for conceptual designs of advanced turbines to different firms/companies. Early in the development of conceptual designs, it became clear that there were significant gaps in the knowledge of fish responses to physical stresses (injury mechanisms) experienced during turbine passage. Consequently, the AHTS program expanded its activities to include studies to develop biological criteria for turbines (Cada, 2001). Additional information about DOE efforts with advanced hydroelectric turbines is available at http://hydropower.inel.gov/turbines/pdfs/amfishsoc-fall2001.pdf.

Case Study: New Turbine Technology at Wanapum Dam, Washington

As the conventional turbines at Wanapum Dam, which were installed in the early 1960s, approached the end of their operating life, the Grant County Public Utility District sought a more efficient and fish friendly design for replacement units. In February 2005, the new turbine technology went online at the Wanapum Dam in Washington state; field testing began immediately. FERC approved the installation in August 2003, after the hydropower industry and the US Department of Energy spent nearly 10 years finalizing the new design.

The new six-bladed turbine showed a 14 % increase in power output and an average 3 % increase in water use efficiency over the conventional Kaplan turbines. Preliminary fish passage test results indicate that the survival rate for migrating fish passing through the dam will improve with the installation of the new turbine. Assuming the testing continues to go well, all 10 Wanapum Dam turbines will be replaced over an eight year period and power output will increase from approximately 900 megawatts to 1,100 megawatts. The estimated cost of all ten turbines is $150 million.

Sources:
Grant County Public Utility District. 2005. *New Turbine Technology Expected to Improve Fish Survival.* http://www.gcpud.org/aboutus/newsreleases/022305newturbinetesting.pdf. Accessed September 2005.

Dennis, J. 2005. PUD optimistic about new turbine test results. *Grant County Journal.* http://www.fwee.org/news/getStory?story=1372. Accessed September 2005.

Transference of Fish Runs

Transference of fish runs involves inducing anadromous fish species to use different spawning grounds in the vicinity of the impoundment. To implement this practice, the nature and extent of the spawning grounds that were lost due to the blockage in the river need to be assessed, and suitable alternative spawning grounds need to be identified. The feasibility of successfully collecting the fish and transporting them to alternative tributaries also needs to be carefully determined.

One strategy for mitigating the impacts of diversions on fisheries is the use of ephemeral streams as conveyance channels for all or a portion of the diverted water. If flow releases are controlled and uninterrupted, a perennial stream is created, along with new instream and riparian habitat. However, the biota that had been adapted to preexisting conditions in the ephemeral stream will probably be eliminated.

Constructed Spawning Beds

When a dam adversely affects the aquatic habitat of an anadromous fish species, one option may be to construct replacement spawning beds. Additional facilities such as electric barriers, fish ladders, or bypass channels would be required to channel the fish to these spawning beds.

Merz et al., (2004) tested whether spawning bed enhancement increases survival and growth of chinook salmon (*Oncorhynchus tshawytscha*) embryos in a regulated stream with a gravel deficit. The authors also examined a dozen physical parameters correlated with spawning sites (e.g., stream velocity, average turbidity, average dissolved oxygen concentration, distance from the dam) and how they predicted survival and growth of Chinook salmon and steelhead (*Oncorhynchus mykiss*). The results suggest that spawning bed enhancement can improve embryo survival in degraded habitat. In addition, measurements of observed physical parameters before and after spawning bed manipulation can accurately predict benefits to target species. NOAA's S*tatus Review of Chinook Salmon from Washington, Idaho, Oregon, and California* (1998) states that artificial spawning beds for ocean-type chinook salmon operated near three different dams was eventually discontinued because of high pre-spawning mortality in adult fish and poor egg survival in the constructed spawning beds. The success of constructed spawning beds in increasing survival and development of fish varies and is often dependent on the site.

Removal of Dams

The removal of dams has become an accepted practice for dam owners to deal with unsafe, unwanted, or obsolete dams. Dam removal may be necessary as dams deteriorate, sediments accumulate behind dams in reservoirs, human needs shift, and economics dictate (NRC, 1992).

> ***Dam Removal Resource***
>
> *American Rivers is a nonprofit organization focusing on the health of U.S. river systems, fish, and wildlife. American Rivers' website hosts a variety of information related to hydromodification, including past and recent estimates of dam removals in the United States.*
> http://www.americanrivers.org

Migratory fish passage throughout United States rivers and streams is obstructed by over 2 million dams and many other barriers such as blocked, collapsed, and perched culverts. The National Oceanic and Atmospheric Administration (NOAA) is expanding its community-based approach to restoring fish habitat through the recently developed Open Rivers Initiative (ORI). Administered by NOAA Fisheries Service Office of Habitat Conservation, ORI is designed to help communities correct fish passage problems by focusing financial and technical resources on the removal of obsolete dams and other blockages. ORI strives to restore vital habitat for migrating fish like salmon, striped bass, sturgeon, and shad, as well as improve community safety and stimulate economic revitalization of riverfront communities. Through its more broadly focused Community-based Restoration Program (CRP), NOAA Fisheries Service has opened over 700 miles of stream habitat with financial and technical assistance provided to fish passage projects. Examples of successfully completed CRP projects that fit the Open Rivers Initiative model include:

- Culvert removal in the John Smith Creek (Mendocino County, CA)
- Mt. Scott Creek dam removal (Happy Valley, OR)
- Wyomissing Creek dam removal (Reading, PA)
- Town Brook dam removal and fish ladder (Plymouth, MA)
- Sennebec dam removal (Union, ME)

Additional information on the Open Rivers Initiative can be found at:
http://www.nmfs.noaa.gov/habitat/restoration/ORI

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 vs. inactive). Dams are used for various purposes, including water supply, hydroelectric power, recreation, and flood control benefits. When proposals are made to remove a dam with one or more of these active functions, the way in which these functions and benefits will be replaced or mitigated must be addressed (FOR, 1999). An example of this process can be seen with the Jackson Street Dam, located on Bear Creek in Medford, Oregon. The dam diverted water from the creek into the irrigation canals of Rogue

River Valley Irrigation District (RRVID). Since the dam created a partial barrier to migratory fish, a loss of stream habitat, and an algae-filled impoundment near the city park, a consensus was reached that removing the dam was the most cost-efficient means of eliminating the problem. However, since the dam was currently providing irrigation diversion, another cost-efficient diversion had to be devised for RRVID. The decision was made to replace the old dam with a less damaging diversion structure. The new structure is approximately one-fourth the height of the Jackson Street Dam (about 3 feet) and located 1,200 feet upstream. The new structure is also removed at the end of the irrigation season, which coincides with the time of the year when most upstream migration occurs. When the new structure is in place during the irrigation season, it allows fish to migrate (by well-designed fish ladders and screens), and it was designed so that little water will back up behind it. It is also equipped with fish screens to keep fish out of the irrigation canal (FOE et al., 1999).

Dam owners are responsible to keep the dam safe. When a dam begins to fail, or breach, a decision must be made as to whether to keep or repair the structure. When a dam generates no revenue, the long-term costs of liability insurance, dam and impoundment maintenance, and operation weigh heavily on the side of dam removal. On average, dam removal costs 3 - 5 times less than repair.

Source: Delaware Riverkeeper, n.d.

It is also important to consider the cost of removing a dam, and who will pay for the removal. Removal costs can vary from tens of thousands of dollars to hundreds of millions of dollars, depending on the size and location of the dam. Who pays for dam removal can be a complex issue. Removal in the past has often been financed by the dam owner; local, state, and federal government; and in some cases agreements where multiple stakeholders cover the costs (American Rivers, n.d.a.). A guide to selected funding sources (*Paying for Dam Removal: A Guide to Selected Funding Sources)* is available from American Rivers at:
http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1729.

In the case of the Jackson Street Dam, the most cost-effective alternative to solving the problems associated with the dam was to remove it. However, since it was currently functioning, an alternative means to provide that function was needed. In some instances, it is not more beneficial to remove the dam if it is functioning. For example, USACE expressed concern over the costs of air pollution created by fuel-burning power plants needed to replace the lost power from dams in the debate over the removal of the Snake River dams (Lee, 1999). There was much controversy over whether it was more cost-efficient to remove the dams, especially due to the functions the dams provided. USACE found that replacing the dams would be costly, both monetarily and ecologically. The estimated costs to replace the lower Snake hydropower were between $180 million to $380 million a year for 100 years (Lee, 1999). In addition, the cost of the resulting increase in pollution due to natural gas or coal replacement plants was very high, yet an actual amount was not determined.

Evaluations made by the USACE found that the costs associated with removing the Snake River dams greatly exceeded the costs of maintaining, improving, and keeping them (Associated Press, 2002). Therefore, the dams along the Snake River remain and are repaired. USACE plans to pursue technical and operational changes at the Snake River dams to improve fish survival, in addition to barging or trucking juvenile salmon around the dams (Associated Press, 2002).

One technological upgrade alternative to removing dams that are blocking fish passage is use of the removable spillway weir (RSW). The RSW, a prototype weir concept, allows juvenile salmon and steelhead to pass the dam near the water surface under lower accelerations and lower pressures, providing a more efficient and less stressful passage route through the dam. The design of the RSW is different from existing spillways whose gates open 50 feet below the water surface at the face of the dam and pass juvenile fish under high pressure and high velocities. The RSW passes juvenile salmon and steelhead over a raised spillway crest, similar to a waterslide, down to the river below. Juvenile fish are safely passed over the weir more efficiently than with conventional spill, while reducing migration delays at the dam. The RSW structure also is designed to be "removable" by controlled descent to the bottom of the dam forebay. This capability permits returning the spillway to original flow capacity during major flood events (USACE, n.d.).

A prototype RSW was installed at Lower Granite Dam on the lower Snake River in 2001. Another RSW is slated for completion in 2005 at Ice Harbor Dam. Additional RSWs are also being considered for Little Goose, Lower Monumental, McNary and possibly John Day dams (USACE, n.d.).

RSWs have the potential to benefit fish and provide power savings to the region because the amount of water used to pass similar numbers of fish is less. Initial biological tests indicate that fish pass over the RSW much more efficiently than under conventional spillway gates. Preliminary tests show that the RSW is 4 or 5 times more effective in fish passage per unit of flow than existing gates. Given the high effectiveness, less spill may be required, which reduces total dissolved gas in the river and improves water quality (USACE, n.d.).

The entire decision-making process is a delicate balance that involves many stakeholders. One important step in this process is to decide if the ecological benefits of removing the dam outweigh the dam's functioning benefits of maintaining the dam. Many agencies spend a great deal of time and effort debating this issue.

When deciding whether to remove a dam, interested parties should collect as much information as possible about the potential removal project. American Rivers has published a fact sheet, which contains a variety of sources to help begin researching the particular dam that might be removed and the river it is located on. The fact sheet is available at http://www.amrivers.org/doc_repository/Reseaching%20a%20Dam%20-%20-%20Data%20Collection.pdf (American Rivers, n.d.b.)

Repercussions of Unsafe Dams (American Rivers, 1999)

Unsafe dams may result in:

1. *Loss of life from surging flows if a dam fails*
2. *Destruction of property*
3. *Harm to the downstream river environment (e.g., erosion)*
4. *Release of toxic sediments (e.g., dioxins, PCBs)*
5. *Risk to users of the river (i.e., users may not be able to avoid life threatening hazards if in close approximation to a failing dam)*
6. *Jeopardizing delivery of critical services to communities (e.g., power generation, flood control)*

American Rivers and Trout Unlimited have published a guide to help decide whether to remove a dam or not. The guide, *Exploring Dam Removal: A Decision-Making Guide* (American Rivers and Trout Unlimited, 2002), is available at: http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1802.

The decision-making process related to dam removal is often complex with inputs from stakeholders with opposing desired outcomes. The following subsections outline some of the complex technical issues that may be associated with an evaluation to remove or keep a dam.

Removal Process

The complexity of the removal process of a dam is specific to each particular case of removal. There are two major components of the removal process: the stakeholders involved in the decision-making process of removing the dam and the actual physical removal of the dam itself. The authorities that govern dams are numerous, yet overlapping. These entities include: USACE, Bureau of Reclamation, Federal Energy Regulatory Commission (FERC), and other federal agencies; interest groups; and state and local governments. There are also various state programs that have been created in order to keep dams safe and environmentally friendly, as well as to financially help owners to remove their dams. A study by the Aspen Institute (2002) provides a list of priority issues to consider when dam removal may be a possibility. Among the considerations listed are dam and public safety, economics, environmental concerns, risk, social values and community interests, scientific information, and stakeholder participation. This report suggests that success of dam removal is dependent upon a thorough analysis of these competing factors and input from all interested parties (Aspen Institute, 2002). Often times, the dam owner makes the decision to remove a dam, deciding that the costs of continuing operation and

Case Study: U.S. Army Corps of Engineers Decides to Keep Dams

In 2002, USACE completed an environmental impact statement and migration feasibility report that detailed the impact of Idaho's lower Snake River dams on endangered fish populations. Following the findings of this report, USACE decided against breaching the four dams on the river. Although some groups favored breaching the dams to create better passage for endangered fish species, the cost/benefit ratio determined by USACE favored keeping the dam. Dam maintenance and the salmon program in this area had an estimated cost of $36.5 million in 2002, but the dams produced $324 million per year in electricity, barge transportation benefits, and water. The USACE made this decision based on the negative economic impacts to the electricity users, lack of conclusion by the U.S. National Marine Fisheries Service as to whether the breech would be necessary, and concerns that sediment trapped behind the dam would wash downstream if the dam was removed. Instead, the USACE decided to put $390 million in technical and operational improvements in order to ensure fish survival. As of 2002, some of the improvements under consideration included the addition of fish ladders and transportation of fish by vehicle around the dams. Other long-term plans included development and implementation of biological rules for flow augmentation and development and implementation of biological rules for smolt transportation, including optimal spill for salmon.

Sources:
Associated Press and the Herald Staff, Tri-City Herald, *Corps Modifying Dams.* http://www.snakedams.com/news/022102.html. Accessed July 2002.

USACE. 2002. *Improving salmon passage: Final Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement.* http://www.nww.usace.army.mil/lsr/final_fseis/study_kit/summary.pdf. Accessed March 2004.

maintenance are greater than the cost of removing the dam. However, state dam safety offices can order for a dam to be removed if there are safety concerns; FERC can order removal of dams under their jurisdiction for environmental and safety reasons (American Rivers, n.d.a.).

Case Study: Removal of Newport No. 11 Dam

FERC recommended the removal of the Newport No. 11 Dam on the Clyde River in Vermont in a June, 1996 environmental impact statement (EIS) against the wishes of the dam owner. The dam was controversial because it was constructed hurriedly in 1957 with no permits, and since then caused yearly erosion, prevented fish passages, and created inadequate flows that led to the dewatering of one-half mile of the river. In 1994, the dam breached under spring rains and snowmelt run-off combined with the long-term erosion problems. Due to the fact that there were other less-harmful dams in the project, FERC felt that this "would provide the necessary balance between the hydropower use and environmental benefits and enhancements." On August 28, 1996, the dam was destroyed by a controlled explosion, and was later removed in its entirety mechanically. This marked the first time in history that a U.S. hydroelectric dam was removed. Dam removal has lead to improved ecological conditions in the river. For example, one source reported that just months after dam removal, some species of fish were beginning to re-inhabit areas where they had not been sighted since the dam was built.

Sources:
American Museum of Natural History. *Science Bulletin: Setting rivers free.* http://sciencebulletins.amnh.org/biobulletin/biobulletin/story1304.html. Accessed March 2004.

Friends of the Earth, American Rivers, and Trout Unlimited. 1999. *Dam Removal Success Stories: Restoring Rivers Through Selective Removal of Dams That Don't Make Sense*. American Rivers, Friends of the Earth, & Trout Unlimited. http://www.earthscape.org/r1/tru03/tru03.pdf. Accessed March 2004.

Friends of the River. 1999. *Rivers Reborn: Removing Dams and Restoring Rivers in California.* Friends of the River, Sacramento, CA. http://www.friendsoftheriver.org/publications. Accessed March 2004.

State governments have authority over the dams in their jurisdiction. Other state and local government agencies dealing with issues such as water quality, water rights, and fish and wildlife protection can also play a role in overseeing dams within their jurisdiction if they so choose (FOE et al., 1999). Certain states have implemented stringent rules for dams that are and are not regulated by FERC or USACE. For example, the state of Wisconsin has a Dam Safety Inspection Program that requires dams to be inspected every 10 years by the Wisconsin Department of Natural Resources (WDNR) (Doyle et al., 2000). Any dam that fails to meet safety requirements set by WDNR must be repaired or removed. The state of Pennsylvania has implemented a law that was written under the order of the Pennsylvania Fish and Boat Commission that states that any newly constructed or existing dam that requires a state permit for construction or modification must also include provisions for fish passage (Doyle et al., 2000).

Case Study: Trout Unlimited Joined the Fight in Getting the Edwards Dam Removed

The Edwards dam, build on Kennebec River in Maine in 1837, was operated for power generation, but the amount of power generated was insignificant. Prior to dam removal in 1999, it produced 3.5 megawatts of electricity, which was only one-tenth of one percent of the entire power supply for Maine. It also significantly destroyed a valuable fishery and prevented migratory fish from passing. When the Edwards Dam license expired in 1993, the dam owner sought a new 30-year license from FERC, but the “Kennebec Coalition,” which was composed of four environmental groups—American Rivers, the Natural Resources Council of Maine, the Atlantic Salmon Federation, and Trout Unlimited—voiced its opinion that the dam should be removed. This action was seen as a test case to determine the importance of river ecosystems to FERC. In the draft EIS in 1996, FERC released its recommendation for regimenting the dam and improving fish passage. However, upon more research, FERC recommended dam decommissioning and removal in its final EIS in July 1997. This decision was supported by the cost analysis, which revealed that in order to provide adequate passage for the targeted species, it would cost 1.7 times more than removing the dam. On November 25, 1997, FERC denied the application for the relicense of Edwards Dam, marking the first time FERC denied an application for relicensing. In May 1998, all parties involved signed an agreement to aid in the process of removing the dam, and dam removal was completed during the summer and fall of 1999. Temporary gravel cofferdams were incrementally set up throughout the summer in 1999, and the dam was breached allowing the river to flow through the openings. The remainder of the dam was removed with heavy construction equipment, with completion on October 12, 1999. In the first year after its removal, migratory fish including alewives (*Alosa pseudoharengus*), striped bass (*Morone saxatilis*), sturgeon and Atlantic salmon (*Salmo salar*) were able to travel from the Atlantic Ocean up the river. The removal also provides a basis for those who argue in favor of removing older dams that are no longer seem sensible.

Sources:

Friends of the Earth (FOE), American Rivers, and Trout Unlimited. 1999. *Dam Removal Success Stories: Restoring Rivers Through Selective Removal of Dams That Don’t Make Sense*. American Rivers, Friends of the Earth, & Trout Unlimited. Available online at: http://www.earthscape.org/r1/tru03/tru03.pdf. Accessed March 2004.

Natural Resources Council of Maine. 2000. One-Year Anniversary of Edwards Dam Removal Celebrated as National Success Story: Kennebec River's Recovery Benefits Wildlife, People and Communities. Available online at: http://www.maineenvironment.org/Edwards_Dam/NewsAnniversaryofEdwards1.htm. Accessed March 2004.

Some states have programs that aid dam owners in the process of removing their structures. The Pennsylvania Department of Environmental Protection (DEP) has adopted procedures to make it easier and less expensive for dam owners to remove unsafe, unused, or unwanted dams. In this process, dam owners of third order or larger streams are contacted and asked if they are interested in removing their dams. If they are, then all the landowners affected by the removal are contacted, and a public meeting is held if interest warrants one. After public comments, an engineering design is created, followed by an environmental assessment, then sediment and erosion control plans are established, and finally approval is sought by the USACE. This program was used in the removal of seven dams on Conestoga River and also in the removal of the Williamsburg Station Dam on the Juniata River. This approval process takes between 12 and 18 weeks (FOE et al., 1999). However, the physical decommissioning and removing of a dam can still be a lengthy and diversified process.

Case Study: Dam Removal for the Environment

In September 2004, in Orange County, New York, a team of engineers from the Nature Conservancy and the Army Corps of Engineers began to remove major parts of the 90-year-old Cuddebackville Dam on the Neversink River. Removal of the dam is part of an effort to save an endangered mussel that is blocked by the dam. The project is the first in New York history where a dam is being removed for purely environmental reasons. The project will remove one of two dams located on either side of an island that splits the Neversink River. The Nature Conservancy does not plan on removing a separate dam on the northeast side of the island because most fish swim up the southwest side. The removal of the steel-reinforced concrete dam is expected to cost about $2.2 million. The Nature Conservancy is paying for 35 percent, and the Army Corps of Engineers is paying for the remainder.

Built in 1915, the dam diverted water down the Delaware and Hudson canal system to turn turbines at a power plant in Cuddebackville, about 65 miles northwest of New York City. In the mid-1940s, the dam was no longer necessary, as the power plant was shut down because modern power lines were built to draw electricity from farther distances.

Once the dam is removed, the depth and speed of the river will not change, but American shad (*Alosa sapidissima*) and native brook trout (*Salvelinus fontinalis*) will be free to swim upstream in the Neversink River, where fly-fishing became popular in the United States. The biggest beneficiary of the dam removal will be the dwarf wedgemussel, a tiny freshwater mussel that is one of the most endangered species in upstate New York. Although the wedgemussel does not swim upstream, host fish that carry its larvae do.

Although many dams are demolished using explosives, the Cuddebackville Dam will not be removed with this approach because of the damage it would cause to the local habitat. Instead, a temporary dam, or cofferdam, was built upstream to divert water to the other side of the island and enable workers to move backhoes and large hydraulic hammers in front to chip at the concrete.

The fish and mussels from the dry side of the island were relocated upstream. Once the dam is removed, the streambed will be restored and water will be released from behind the cofferdam.

Source: Urbina, I. 2004. Dam builder tries new role: dam breaker. *New York Times*, September 22, 2004.

Permitting Requirements for Removing Dams

Removing a dam requires permits from state, federal, and local authorities. These permits are typically required to ensure that the removal is done is a manner that is safe and minimizes short and long term impacts to the river and floodplain. States and local governments have different permit requirements. The following federal permits may be required for dam removal:

- Clean Water Act (CWA) Section 404 Dredge and Fill Permit
- Rivers and Harbors Act Permit
- FERC License Surrender or Non-power License Approval
- National Environmental Policy Act (NEPA) Review
- Federal Consultations
- Endangered Species Act Section 7 Consultation
- Magnuson-Stevenson Act Consultation
- National Historic Preservation Act Compliance
- State Certifications
- Water Quality Certification
- Coastal Zone Management Act Certification

The following state permits might be required for dam removal:

- Waterway Development Permits
- Dam Safety Permits
- State Environmental Policy Act Review
- Historic Preservation Review
- Resetting the Floodplain
- State Certifications

The following municipal permits may be required for dam removal:

- Demolition Permits
- Building Permit

Tips for a Successful Permitting Process (American Rivers, 2002b)

Dam removal is relatively new and the permitting process can be difficult. Most state and federal agencies are not yet practiced at moving a restoration project such as dam removal through the permitting process. The relevant permitting requirements were designed for more destructive activities, and dam removal does not easily fit into the requirements. Tips to help make the process smoother include:

Schedule Time

- Expect dam removal projects to take longer than construction efforts.
- Schedule more lead-time into the permitting process to avoid delays and frustrations.

Establish a Relationship with the Permitting Agencies

- Hold a pre-application meeting with key agency staff, as soon as you have your project well thought out.
- Do not attempt to circumvent the process and stick with the permitting timeline.
- Do not provide inconsistent information.
- A single point of contact for the group applying for the permit will help avoid confusion and maintain communication.

Providing Information About the Proposed Project

- Create clear and simple descriptions and drawings (to scale) of the proposed project.
- Be sure to identify complicating conditions, schedules, seasonal constraints, etc.
- Provide and discuss alternatives, but make it clear why the chosen approach should be used.
- Assume the reviewers know nothing about your project.

Sediment Removal Techniques

Large dams can trap thousands to millions of cubic yards of sediment over time, eliminating the flood control or storage capacity of the dam. Removal or control of sediment behind a dam can represent a large portion of the cost and planning effort of a dam removal project. There are several methods available to project planners and dam owners that target different pollution concerns and budgetary limitations (International Rivers Network, 2003). The options in terms of sediment removal range from complete removal and relocation of all accumulated material from the inundated regions; removing sediment only from the anticipated channel of the river, or allowing the river to erode a new channel through the sediment (Wunderlich et al., 1994).

If the sediment is basically clean and the main concern is turbidity and clogging downstream streambed spawning areas, gradual incremental drawdowns of the reservoir behind the dam allow the sediment to be transported downstream in smaller portions and avoids the release one large, lethal volume of sediment.

If contaminated sediment is the main concern, dredging is an option that can be used. While the use of silt curtains can minimize turbidity during dredging, silt curtains do not contain dissolved substances such as metals, which can pose a threat to downstream ecosystems (EMC2, 2001). Another option for contaminated sediments is to stabilize the sediment in place within the stream. This can be accomplished by leaving a portion of the dam in place to hold back an area of sediment that is of concern. The strategic placement of boulders can also contain the sediment from moving downstream.

In certain cases, the use of hydraulic dredging and dewatering is a necessary process. For example, the Lower Fox River in Wisconsin has become contaminated with PCB laden sediment from industrial, municipal, and other discharges into the river. The Wisconsin Department of Natural Resources in cooperation with several other partners is undertaking a sediment removal demonstration project. The proposed method of sediment removal involves hydraulic dredging of contaminated sediment, on-shore dewatering (removing water from the sediment), water treatment, and the transportation and disposal of PCB-containing sediments.

The contaminated sediment in the Lower Fox River will be removed from the river bottom through a process known as hydraulic dredging which is likened to an “underwater vacuum.” The hydraulic dredge pumps a mixture of sediment and water through a pipe to a temporary on-shore dewatering facility where water is mechanically removed from the dredged sediments. Settling basins contain the sediment and water mixture, while the dewatering and water treatment facilities process the dredged materials. After the solids settle out of the mixture, the thickened sludge is pumped to the mechanical dewatering equipment (e.g., belt presses). Thereafter, the dewatered solids are solidified with a drying agent (e.g., lime) to prepare for transportation and disposal. The water from the settling and dewatering processes is pumped from the settling basins to an engineered water treatment system for removal of particulates and PCBs. The treated water can then be discharged to the Lower Fox River in accordance with a state permit. After dewatering and solidification, the sediments are loaded into trucks and then transported to an approved landfill (Montgomery Watson, 2001).

To further minimize downstream impacts, sediment removal work can be conducted during low-flow conditions. The use of temporary cofferdams or diversion channels or tunnels diverts flow during sediment management activities and dam removal operations and minimizes erosion. Silt fencing can be installed at the water’s edge to prevent newly exposed sediments from re-entering the stream. The fencing should be maintained until the sediment is removed or stabilized by vegetation (Montgomery Watson, 2001).

Physical Changes Associated with Dam Removal

Removing a dam affects the flow of water, movement of sediment and chemical constituents, and the overall channel morphology (Academy of Natural Sciences, 2002) on the waterway where the dam was located. The impacts of removing a dam differ for the upstream and downstream sections of a waterway.

Upstream Impacts

The removal of a dam allows the water formerly held behind the dam to flow and will likely cause the extent of the impoundment area or reservoir area to decrease. As a dam is removed and the water recedes, sediment is scoured from the bottom and the stream channel returns to its pre-dam pathway or a newly carved channel. As a channel is formed, areas that were formerly beneath the impoundment area become exposed. This can leave large areas of unvegetated and unstable land exposed, which makes these areas likely to undergo erosion and gully development, increasing the sediment load to the stream.

In time, vegetation will stabilize the newly formed stream banks, reducing erosion and allowing sediment transport levels to return to natural levels. The nutrient and metal constituents associated with the sediment will also return to natural levels. As the newly established channel-like flow develops and the stagnant and deep conditions are removed, the natural temperature and oxygen levels will be reestablished.

Downstream Impacts

Once the physical barrier of the dam is removed, a river can flow unrestricted. As the channel is reformed, the water discharge volume and the stream channel can reach equilibrium. As a result, a more natural stream flow rate is maintained.

With the removal of a dam, the fate of the sediments is of concern because flooding and pollution problems can result. On a short term time scale, the redistribution of the fine silt and sand sediments that accumulated behind the dam wall may cause an increase in turbidity and water quality problems. In addition, the impact can be greater if the sediments contain toxic pollutants, such as mercury and PCBs. After a dam is removed and the sediment that has been trapped behind the dam is redistributed, natural sediment transport levels return. As a result, the constituents typically sorbed to sediment, including nutrients and metals, are no longer found in excess. Normal sediment transport levels typically result in a river bottom with a higher percentage of rocky substrate. Gravel and cobblestones located below the sediment may be exposed or may be transported from upstream locations as the flow rate of the river increases. This unrestricted flow and transport of sediment and gravel plays a key role in restoring sediments to downstream locations and coastal beaches (USDOI, 1995 in American Rivers, 2002a).

Downstream of a dam, the water originates from the bottom of the reservoir as tailwater releases. In stratified reservoirs this water is often devoid of oxygen and well below the stream’s natural temperature. The removal of a dam and the return of natural flow rates will restore a river's natural water temperature range and oxygen levels (Pawlowski and Cook, 1993 in American Rivers, 2002a).

One of the possible short-term effects of dam removal is water supersaturated with nitrogen gas. This often occurs during periods of undersaturation of oxygen. Supersaturation occurs if there is a change in pressure or temperature, which lowers the solubility of the gas. Supersaturated conditions can negatively impact aquatic animal populations and is discussed in greater detail in the biological changes section below (Soderberg, 1995).

Biological Changes Associated with Dam Removal

Changes in the biological community following the removal of a dam are difficult to generalize, as they are highly site specific and can vary in recovery time from a few months to decades or even centuries. With the removal of a dam, there are changes in the vegetative community surrounding the stream channel and changes in the biological community within the stream itself. According to Friends of the River (1999), "unblocking rivers is a tried and true river and fish restoration tool." The U.S. Fish and Wildlife Service and the California Fish and Game Department consider dam removal a practice for restoring fisheries and habitat (Friends of the River, 1999). The upstream and downstream impacts of dam removal vary and are described in greater detail below.

Upstream Impacts

Following the removal of a dam, a return to the normal temperature range, flow rates, and oxygen levels supports the return of native aquatic vegetation species. Still water impoundments support aquatic vegetation that is free floating or that does not need to be strongly rooted, while free-flowing systems support plants that are rooted strongly enough to resist being uprooted by the water current (WRM, 2000).

As the water recedes and the formerly impounded area becomes exposed, vegetation can begin to colonize the area. The exposed area is likely to be colonized by invasive plant species. The vegetation that initially colonizes the newly exposed sediment in the former impoundment area is often able to remain for several years and prevent other vegetation from entering the area. In some cases, plants that initially colonized newly exposed sediments following the removal of a dam are able to maintain colonization of the area, out competing native plant species (Doyle et al., 2000). A planting scheme of native plant species that is installed after the reservoir is drawn down and that is aggressively maintained may help avoid the problem of invasive species colonization. In areas where dam removal allows tidal waters to reach the upstream sections, the salt water often aids in warding off the intrusion of invasive species.

The removal of a dam and the subsequent drawdown of water from the impoundment area can affect the wetlands formerly bordering the impoundment area. As the dam is removed, the water table typically begins to drop. The elevation of the wetlands and the extent of the water table drawdown determine whether the wetland areas dry up and what changes will occur in the wetland species composition. Wetlands that develop alongside the newly carved channel are likely to be different than the wetlands formerly bordering the impoundment area in terms of plant and animal species composition.

The biological changes associated with the removal of a dam can be described in phases, as the water body makes the transition from reservoir to river. This includes a pattern of relatively rapid recovery for invertebrates or short-lived taxa, followed by a second phase of slower recovery for fish or longer-lived taxa if the dam removal is not an especially large or disruptive event. Overall, the initial impacts determine the ecological recovery that follows (Doyle et al., 2000).

In general, the removal of a dam results in rejuvenated fisheries and improved water quality (Trout Unlimited, n.d.). The restoration of natural flow fluctuations causes biodiversity and population density of native aquatic organisms to increase (American Rivers, 2002a). Dam removal allows for improved fish passage and unrestricted fish movement that provides access to spawning habitat upstream. For coastal rivers, the removal of a dam allows tidal waters to reach upper portions of the stream that were formerly cut off by the dam, creating a spawning environment preferred by certain fish species (Dadswell, 1996 in American Rivers, 2002a). Access to upstream sections is particularly beneficial for anadromous fish that live most of their lives in saltwater and swim upstream toward freshwater to spawn (Massachusetts River Restore Program, 2002).

Dam removal often displaces warm-water species that prefer lake-like conditions and promotes the recovery of fish populations that prefer cold-water rivers, such as salmon, trout, shad, river herring (*Alosa chrysochloris*), striped bass (*Morone saxatilis*), sturgeon, and alewife (*Alosa pseudoharengus*) (Department of the Interior 1995 in American Rivers, 2002a). Dam removal also results in a decrease in fish mortality for species that no longer need to migrate through a dam (American Rivers, 2002a).

The biological linkages that are broken with the installation of a dam can be re-established with removal of the dam (Academy of Natural Sciences, 2002). Fish play an important role within the food web as both predator and prey. They also play an important role in nutrient cycling and movement, through migration and excretion. The removal of a dam blocking fish movement will allow fish to remain as a link in the food web upstream as well as continuing to aid in the movement of nutrients (Academy of Natural Sciences, 2002).

A dam can act as a barrier between upstream and downstream fish populations. If a downstream community of fish is contaminated with a toxin, that population is physically separated from the upstream community. The same argument can be made for an exotic fish species that enters a stream system. Whether the species is upstream or downstream, it is separated physically from the other section of the stream (American Rivers, 2002a). Thus, the removal of the dam can negatively impact the ecosystem if it allows for the movement of a population contaminated with toxins or the expansion of an invasive species population that was previously prevented from traveling to a section of the stream because of the presence of a dam.

In addition to fish populations, dam removal may affect algal biomass levels, as nutrient levels may be increased or decreased, depending on the relative extent to which the impoundment and the newly exposed sediments were a nutrient sink. The species composition of the algal population may be altered by the changes in flow rate, discharge volume, water temperature, and light availability (Academy of Natural Sciences, 2002). The abundance and diversity of benthic macroinvertebrates is also affected by the physical and chemical processes that occur from dam removal (Academy of Natural Sciences, 2002).

Freshwater mussels are sometimes reliant upon fish to complete their life cycles. The removal of a dam that allows fish to freely migrate upstream, aids in the rejuvenation of the declining freshwater mussel population. Due to a lack of mobility, fresh water mussels are especially sensitive to water quality degradation and are an indication of local water conditions.

Downstream Impacts

Downstream of the former dam, wetlands are likely to reappear along side the stream channel where they occurred prior to the construction of the dam (WRM, 2000). Dam removal restores natural flows downstream, including periodic flooding of adjacent terrestrial areas, which benefits wetlands bordering streams and rivers (Kaufman 1992 in American Rivers, 2002a). Revegetation of river beds and banks typically occurs within one growing season, following removal of a dam (Massachusetts River Restore Program, 2002). In general, the removal of a dam favors the recovery of native organisms (American Rivers, 2002a).

Recolonization of the stream banks by vegetation affects the biological community within the stream by providing shade, reducing water temperatures, and supplying a source of woody debris and organic matter to the stream.

On a short-term time scale, the redistribution of the fine silt and sand sediments increases the turbidity and can damage spawning grounds, water quality, habitat, and food quality (American Rivers, 2002a). Suspended sediment loads can have a negative impact on a biological community and reach lethal levels during dam removal if preventive measures are not implemented (Doyle et al., 2000). If the sediments contain toxic pollutants, such as mercury or PCBs, the impact can be greater. However, all of the impacts associated with sediment redistribution are often temporary (American Rivers, 2002a).

Short-term chemical changes to the water quality, including the possibility of supersaturation of nitrogen gas directly following the removal of a dam, can cause aquatic animals to experience adverse conditions. This can include gas bubble disease, in which nitrogen bubbles form in the blood and tissues and block capillaries by embolism (Soderberg, 1995 and Colt, 1984). Adverse effects can be seen when the dissolved nitrogen level reaches 102% and at 105% widespread fish mortalities are possible (Dryden Aqua, 2002). Supersaturation was an issue in the removal of Little Goose Dam on the Snake River, which was removed in 1992. It occurred after the dam was removed and many fish and insects perished (American Rivers, 2002a). If a reservoir is drawn down slowly, the severity of the impact of supersaturation on aquatic organisms is lessened (American Rivers, 2002a).

As streamside vegetation begins to recover and suitable habitat is restored, fish begin to return (Pennsylvania Fish and Boat Commission, 2001). Changes in flow as a result of dam removal lead to the development of side channels and ponds that provide habitat for fish and wildlife. Increased flow rates also allow for the transport of larger debris, including gravel and logs, which create spawning beds and pool and riffle habitat (River Recovery, 2001). In addition, the rocky substrate environment that is typically exposed as a result of dam removal provides habitat for aquatic insects and spawning fish. Eventually, a decrease in species that flourished in the sediment free waters below the dam outlet is likely to occur (Department of the Interior 1995 in American Rivers, 2002a). In the long term, the return to natural stream temperatures, oxygen levels, and flow rates all contribute to the reestablishment of a healthy aquatic and riparian ecosystem.

Additional resources for dam removal include the following websites:

- Academy of Natural Sciences: http://www.acnatsci.org/research/pcer/manatawny.html
- American Rivers' Rivers Unplugged Program: http://www.amrivers.org; http://www.amrivers.org/index.php?module=HyperContent&func=displayview&shortname=riversunplugged
- Association of State Dam Safety Officials: http://www.damsafety.org
- Friends of the Earth's River Restoration: http://www.foe.org/camps/reg/nw/river/index.html
- Friends of the River's River Reborn Program: http://www.friendsoftheriver.org/Publications/RiversReborn/index.html
- International River Network's River Revival Program: http://www.irn.org/revival/decom
- Massachusetts Department of Fisheries, Wildlife, and Environmental Law Enforcement River Restore Program: http://www.mass.gov/dfwele/river/rivrestore.htm
- National Performance of Dams Program Stanford University: http://www.stanford.edu/group/strgeo/researchcenters.html
- New Hampshire Department of Environmental Services: http://www.des.state.nh.us/dam.htm
- Pennsylvania Department of Environmental Protection, Division of Dam Safety, Dam Safety Program: http://www.dep.state.pa.us/dep/deputate/watermgt/we/damprogram/Main.htm
- Pennsylvania Fish & Boat Commission: http://www.fish.state.pa.us
- River Alliance of Wisconsin's' Small Dams Program: http://www.wisconsinrivers.org/SmallDams/prog_dams.html
- River Recovery – Restoring Rivers through Dam Decommissioning: http://www.recovery.bcit.ca/index.html
- Trout Unlimited's Small Dams Campaign: http://www.tu.org/small_dams
- United States Society on Dams: http://www.ussdams.org

- Wisconsin Department of Natural Resources: http://www.dnr.state.wi.us/org/water/wm/dsfm/dams/removal.html

Other resources include the following:

- Bednarek, A.T. 2001. Undamming rivers: A review of the ecological impacts of dam removal. *Environmental Management* 27(6):803-814.
- Bioscience. 2002. Dam removal and river restoration: Linking scientific, socioeconomic, and legal perspectives. Summer (special issue).
- Born, S.M., et al. 1998. Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environmental Management* 22(3):359-370.
- Heinz Center. 2002. *Dam Removal: Science and Decision Making*. Available at: http://www.heinzctr.org/Programs/SOCW/dam_removal.htm.
- International Rivers Network: http://www.irn.org/pubs/wrr
- Niemi, G.J., et al. 1990. Overview of case studies on recovery of aquatic systems from disturbance. *Environmental Management* 14(5):571-587.
- Trout Unlimited, Small Dams Campaign, Dam Removal Success Stories: http://www.tu.org/small_dams/removal/3a-removal.html
- United States Society on Dams Publications: http://www.ussdams.org/pubs.html
- University of Wisconsin-Madison/Extension. 1996. *The Removal of Small Dams: An Institutional Analysis of the Wisconsin Experience*. Extension Report 96-1, May. Department of Urban and Regional Planning.
- Wisconsin Department of Natural Resources Projects: http://www.dnr.state.wi.us/org/gmu/sidebar/iem/lowerwis/index.htm#baraboo or http://www.dnr.state.wi.us/org/gmu/lowerwis/baraboo.htm; http://www.dnr.state.wi.us/org/gmu/sidebar/iem/milw/index.htm; http://www.dnr.state.wi.us/org/gmu/sidebar/iem/superior/index.htm; http://www.dnr.state.wi.us/org/gmu/sidebar/iem/sheboygan/index.htm
- Billington Street Dam Removal at Town Brook and Old Berkshire Dam Removal: http://www.mass.gov/dfwele/river/pdf/rivtownbrook.pdf and http://www.mass.gov/dfwele/river/pdf/rivwinsert.pdf
- Dam Removal Research at Purdue: http://www.eas.purdue.edu/geomorph/damwebpage.html

Section 3 Streambank and Shoreline Erosion

Figure 3.1 Shoreline Erosion: Before and After Photos
(Source: http://www.dcr.state.va.us/sw/seas.htm)

Streambanks and shorelines naturally erode. Water flowing along (parallel to) streambanks dislodges sediment and other materials that constitute the streambank. Similarly, water flowing perpendicular to shorelines, due to waves or tides, transports sediment and other materials away from the shoreline. Anthropogenic influences change the natural erosion processes, often increasing erosion locally and sedimentation downstream, along adjacent shorelines, or offshore. Many human activities change the hydraulic characteristics of stream flows or transfer energy to adjacent shorelines and contribute to increased streambank and shoreline erosion, for example:

- **Urbanization** that leads to changes in imperviousness creates changes in the hydraulics of water during wet weather events. Increased imperviousness can result in flashier runoff events that are shorter in duration with greater flow rates and more erosive force.
- **Agricultural practices**, such as drainage ditches, can change the characteristics of subsurface water flows into receiving streams. These changes result in less subsurface water storage and often increase stream flows during and after storms.
- **Livestock grazing** may reduce vegetative cover, which can result in more erosion on uplands and increased sediment and other pollutant loads in streams. Livestock that are allowed direct access to streams can significantly increase streambank erosion and destroy important riparian habitat.
- **Roads** built in rural areas, such as forest and recreational roads, alter the natural landscape and can destroy riparian habitat. If not properly installed and maintained, these types of roads erode and supply increased sediment and pollutants to adjacent streams. Additionally, roads may increase imperviousness, which leads to flashier runoff events. Stream crossings associated with rural roads can block fish passage, trap debris during storms, and lead to increased streambank erosion in nearby areas.
- **Marinas** can alter local wave and tidal flow patterns, resulting in transference of wave and tidal energy to adjacent shorelines.
- **Channelization or channel straightening** sometimes results in an increase in the slope of a channel, which causes an increase in stream flow velocities. Channel modifications to reduce flood damage, such as levees and floodwalls, often narrow the stream width,

increasing the velocity of the water and thus its erosive potential. In addition, newly constructed banks are generally more prone to erosion than “seasoned” banks and are more likely to require bank stabilization.

- **Dams** alter the flow of water, sediment, organic matter, and nutrients, resulting in both direct physical and indirect biological effects. The impact of a dam on a stream corridor can vary, depending on the purposes of the dam and its size in relation to stream flow. Varying discharges released from a hydropower dam can be a significant factor increasing streambank erosion. When dams are a barrier to the flow of sediment and organic materials, the decreased suspended sediment load in release waters leads to scouring of downstream streambeds and streambanks.

Case Study: Disappearing Sand on California Beaches

In recent decades, California’s beaches have been disappearing. Seventy to ninety percent of sand on California beaches comes from inland rivers, but dams and seawalls block sediment from being carried to the coast. Constructed between 1850 and 1970, California’s 1,400 dams have trapped millions of tons of sand-laden sediments. Sea walls can also be a threat to beaches. Twenty percent of the sand on beaches comes from the natural erosion of bluffs. Building seawalls stops this erosion and instead accelerates the loss of sand on beaches.

In 1999 Friends of the River (FOR) published a report on dam removal entitled *Rivers Reborn*, which outlines the growing body of scientific evidence that removing some dams can lead to riparian restorations that are feasible and economically beneficial. FOR’s report includes information on two in Southern California are of special interest to surfers. Just upstream from Malibu, one of California’s most famous surfing beaches, is the 100 foot high Rindge Dam, built in 1926. The reservoir behind the dam is now completely filled with sediment. FOR report estimates that the dam traps between 800,000 and 1,600,000 cubic yards of sand and sediment. In addition to trapping sediment, the dam has been cited as an impediment to steelhead fish passage as well as to natural flow conditions. 1999 estimates for removing the dam and trapped sediment range from $4 million to $18 million. The USACE, with matching funds from California State Parks and local agencies, will examine the utility of removing Rindge dam and restoring Malibu Creek. This study should be completed by 2005.

Sources:
Becher, B. 2002. New Study Could Bring Back Steelhead: Returning the Fish to Malibu Creek Still a Dam Problem. *Daily News of Los Angeles*. Page S13.

Caughlan, R. 2000. *Damn the Torpedoes and Torpedo the Dams: Surfers in Danger of Becoming the Beachless Boys*. EcoIQ Magazine. http://www.ecoiq.com/magazine/opinion/opinion61.html. Accessed June 2003.

Friends of the River. 1999. *Rivers Reborn: Removing Dams and Restoring Rivers in California.* http://www.friendsoftheriver.org/Publications/PDF/RiversReborn.pdf. Accessed March 2004.

U.S. Army Corps of Engineers. 2002. *National Regional Sediment Management Demonstration Program, South Pacific Division, State of California*. http://www.spd.usace.army.mil/csmwonline/rsm-spd-april02.pdf. Accessed March 2004.

In summary, these anthropogenic factors can affect the state of equilibrium in streams or along shorelines. The typical chain of events that follows the disturbance to a stream corridor or shoreline can be described as changes in:

- Hydrology
- Stream hydraulics

- Morphology
- Factors such as sediment transport and storage
- Alterations to the biological community

Shorelines can also experience increased rates of erosion as a result of hydromodification activities. Alterations to the sediment sources for beaches can result in erosion. The sediment supplied to beaches or shorelines can come from a variety of sources including rivers, cliff and rocky foreshores, the seafloor, or windblown hinterland dune materials. Beaches and shorelines at the mouth of a river are often replenished by fluvial sediment. When changes within the river system decrease the sediment load carried to the mouth of the river, the result may be decreased sediment supplies to the shoreline or beach. While the design of each hydromodification system determines the impacts that will ensue, streambank and shoreline erosion is a common consequence.

As evidenced by the examples above, many activities can have a profound effect on the stability of streambanks and shorelines. Section 3 outlines some of the techniques available to stabilize streambanks and shorelines affected by these types of activities.

Case Study: Shore Erosion Control

Shore Erosion Control, a Maryland Department of Natural Resources program, was established in 1968 by Maryland's General Assembly to address shoreline and streambank erosion along the Chesapeake Bay and its tributaries. In a 2000 report by the Shore Erosion Task Force, 1,341 miles of nearly 4,360 miles of tidal shoreline within Maryland’s portion of the Chesapeake Bay watershed were identified as eroding. The Task Force also determined that erosion was a problem in all 16 coastal counties along the Chesapeake Bay and in all Coastal Bays watersheds. Problems associated with shoreline and streambank erosion include loss of land and the reduction of riparian buffer areas and wildlife habitat, and sediment deposition in the waters of Maryland. Estimates from 2002 indicated that approximately 5.1 million cubic yards of sediments are delivered annually to the Chesapeake Bay. Deposited sediment is associated with problems such as increased nitrogen and phosphorus input into the Bay, and dredging may be required to removed excess sediments.

The Shore Erosion Control program provides technical and financial assistance to Maryland property owners in resolving shoreline and streambank erosion problems, both through structural (e.g., barrier type structures) and non-structural (e.g., improvements of vegetated areas) controls. Since 1968, Shore Erosion Control has provided technical assistance to Maryland’s property owners and established more than 800 structural projects and 325 non-structural projects. These projects have resulted in more than 483,000 tons of sediment retained.

Sources:
MDNR. 2002. *Shore Erosion Control*. Maryland Department of Natural Resources. http://www.dnr.state.md.us/grantsandloans/secintro.html. Accessed March 2004.

MDNR. 2000. *State of Maryland Shore Erosion Task Force, Final Repor*t. Maryland Department of Natural Resources. http://www.dnr.state.md.us/download/shoreerosion.pdf. Accessed April 2004.

Management Measure for Eroding Streambanks and Shorelines

Management Measure
1) 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, and offshore bathymetry, and the potential adverse impact on other streambanks, shorelines, and offshore areas. 2) Protect streambank and shoreline features with the potential to reduce NPS pollution. 3) Protect streambanks and shorelines from erosion due to uses of either the shorelands or adjacent surface waters.

A. Introduction

Several streambank and shoreline stabilization techniques will be effective in controlling coastal erosion wherever it is a source of nonpoint pollution. Techniques involving marsh creation and vegetative bank stabilization (“soil bioengineering”) will usually be effective at sites with limited exposure to strong currents or wind-generated waves. In cases with increased erosional forces, an integrated approach that employs the use of structural systems in combination with soil bioengineering techniques can be utilized. The use of harder, more structural approaches, including beach nourishment and coastal or riparian structures, may need to be considered in areas facing severe water velocities or wave energy. In addition to controlling the sources of sediment contributed to surface waters, which are causing NPS pollution, these techniques can halt the destruction of wetlands and riparian areas located along the shoreline~~s~~. Once affected streambanks and shorelines are protected, they can serve as a filter for surface water runoff from upland areas, or as a temporary sink for nutrients, contaminants, or sediment already present as NPS pollution in surface waters.

Stabilization practices involving vegetation or engineering structures should be properly designed and installed. These techniques should be applied only when there will be no adverse effects to aquatic or riparian habitat, or to the stability of adjacent shorelines. Finally, it is the intent of this measure to promote institutional measures that establish minimum setback requirements or measures that allow a buffer zone to reduce concentrated flows and promote infiltration of surface water runoff in areas adjacent to the shoreline.

Stream-friendly Project Tips

Before Construction
Involve your neighbors to increase project success
Get the necessary permits
Flag and avoid disturbing wetlands
Preserve existing native trees and shrubs
Cut trees and shrubs rather than ripping them out of the ground (many may resprout)
Make a plan to replant disturbed areas and use native plants
Install sediment-control practices (e.g., coffer dams)

During Construction
Stockpile fertile topsoil for later use for plants
Use hand equipment rather than heavy equipment
If using heavy equipment, use wide-tracks or rubberized tires
Work from the streambank, preferably on the higher, non-wetland side
Avoid instream work except as authorized by the Oregon Department of Fisheries and Wildlife
Stay 100 feet away from water when refueling or adding oil
Avoid using wood treated with creosote or copper compounds

After Construction
Keep out people and livestock during plant establishment
Check project after high flows
Water plants during droughts
Control grass until trees and shrubs overtop grass, usually two to three years

Source: SWCD. No date. *Protecting Streambanks from Erosion: Tips for Small Acreages in Oregon*. Washington County Soil and Water Conservation District and the Small Acreage Steering Committee, Oregon Association of Conservation Districts. http://www.oacd.org/fs04ster.htm. Accessed June 2003.

The initial consideration when faced with the need for streambank restoration is whether a complete removal or reversal of the causative effects is possible. For example, when evaluating restoration sites affected by dams, an initial consideration should be whether changes in operations are possible. Then management measures to improve existing erosion damage should be examined. The alteration of operation approaches in combination with best management and restoration efforts can reduce future impacts. Although dam removal may be the only way to fully restore a stream and its corridors back towards a pre-impounded state, the impacts of dam removal need to be carefully assessed and thoroughly considered before proceeding (FISRWG, 1998). Similarly, removal of channelization structures may allow for a greater recovery of the integrity of a stream corridor. If feasible, the objective of a restoration design should be to eliminate or moderate disruptive influences to allow for equilibrium (NRC, 1992). If this is not possible, restoration may have limited effectiveness in the long term or may require a closer look at an entire watershed to determine alternate restoration activities.

A glossary of stream restoration terms is available from U.S. Army Corps of Engineers' Ecosystem Management and Restoration Research Program at http://el.erdc.usace.army.mil/elpubs/pdf/sr01.pdf.

This management measure was selected for the following reasons:

- Many anthropogenic activities can destabilize streambanks and shorelines, resulting in erosion that contributes significant amounts of NPS pollution in surface waters.
- The loss of coastal land and streambanks due to shoreline and streambank erosion results in reduction of riparian areas and wetlands that have NPS pollution abatement potential.
- A variety of activities related to use of shorelands or adjacent surface waters can result in erosion of land along coastal bays or estuaries and loss of land along rivers and streams.

Preservation and protection of shorelines and streambanks can be accomplished through many approaches, but preference in this guidance is for nonstructural practices, such as soil bioengineering and marsh creation, where their use is appropriate.

Case Study: He'eia Coastal Restoration Project

He'eia State Park is located on an elevated peninsula on the shores of Kaneohe Bay on Oahu, Hawaii. Bordering the park are a unique fringing reef, a mountain stream, and an ancient Hawaiian fishpond. In 2000 the State's Department of Health designated Kaneohe Bay a Water Quality Limited Segment because of the NPS pollution, specifically sediments and nutrients. Kaneohe Bay and He'eia Stream are part of Koolaupoko watershed, which was designated a priority watershed in need of restoration in Hawaii's 1998 Unified Watershed Assessment (UWA) Plan. In the UWA, Koolaupoko watershed was found not to be meeting water quality and other resource goals and was designated a priority watershed in an effort to reduce NPS runoff, and thus enhance recreational use of streams and nearshore waters. Alien coastal plants were causing problems by preventing adequate filtering of waters that emanate from the watershed above before they entered the bay.

Replacing alien plants with native species
The major goal of the project was to expand and enhance the He'eia stream and coastal area by replacing existing alien coastal plants with native strand species. The area was surveyed and plans were developed for removing the alien plants. The project was very successful in removing alien flora, such as mangrove, from the streambanks and in planting native species, such as milo, naupaka, kou ,and puhala in their place. The native species are expected to provide continuous protection to Kaneohe Bay by filtering waters that come from the watershed above. Establishment of the native plants has helped to stabilize streambanks and mitigate erosion.

Benefits to waters and the community
Students and professors from local colleges monitor the water quality of He'eia Stream at multiple sites in the watershed. This restoration project was part of a larger master planning effort to rehabilitate portions of the entire He'eia watershed. The success of this project has given Friends of He'eia State Park a huge boost in their continuing efforts throughout the watershed. The total cost of this project was $155,000; funding included $60,000 in Clean Water Act Section 319 grant funds. An additional Section 319 grant has been awarded to Friends of He'eia State Park to continue this riparian restoration project, water quality monitoring, curriculum development, and public education through August 2005.

Sources:
Hawaii Department of Health. 1998. *Hawai'i Unified Watershed Assessment*. State of Hawaii, Department of Health, Clean Water Branch, Polluted Runoff Control Program.

Hawaii Department of Health. 2000. *2000 305(b) Report, Appendix A: Water Quality Limited Segments*. http://www.hawaii.gov/health/environmental/water/cleanwater/reports/2000-305b/index.html. Accessed December 2005.

USEPA. 2002. *He'eia Coastal Restoration Project: Thousands of Volunteers Replace Alien Plants with Native Species*. U.S. Environmental Protection Agency, Section 319 Success Stories. http://www.epa.gov/owow/nps/Section319III/HI.htm. Accessed June 2003.

B. Management Practices

The management measure generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. A variety of nonstructural and structural practices are presented and are examples of activities that can be used as a single practice or in combination with other practices to achieve the desired project goals. USACE published *Stream Management* (Fischenich and Allen, 2000), which provides a good summary of nonstructural and structural practices as well as a comprehensive review of processes related to stream and streambank erosion, The document also presents a thorough overview of planning activities for approaching streambank erosion issues. The practices described below can be applied successfully to implement the management measure described above.

Nonstructural Practices

Soil bioengineering is used here to refer to the installation of living plant material as a main structural component in controlling problems of land instability where erosion and sedimentation are occurring (USDA-NRCS, 1992). Soil bioengineering can be defined as, “the use of live and dead plant materials, in combination with natural and synthetic support materials, for slope stabilization, erosion reduction, and vegetative establishment” (FISRWG, 1998). Soil bioengineering largely uses native plants collected in the immediate vicinity of a project site. This ensures that the plant material will be well adapted to site conditions. While a few selected species may be installed for immediate protection, the ultimate goal is for the natural invasion of a diverse plant community to stabilize the site through development of a vegetative cover and a reinforcing root matrix (USDA-NRCS, 1992).

Basic principles of soil bioengineering include the following (USDA-NRCS, 1992):

- Fit the soil bioengineering system to the site
    - Topography and exposure (e.g., note the degree of slope, presence of moisture)
    - Geology and soils (e.g., determine soil depth and type)
    - Hydrology (e.g., calculate peak flows in the project area)
- Retain existing vegetation whenever possible
- Limit removal of vegetation
- Stockpile and protect topsoil
- Protect areas exposed during construction
- Divert, drain, or store excess water

Additional information about soil bioengineering principles is available from the *Engineering Field Handbook, Chapter 18* (USDA-NRCS, 1992). Local agencies, such as the USDA Natural Resources Conservation Service (NRCS) and the Cooperative Extension Service, can be a useful source of information on appropriate native plant species to consider in bioengineering projects. Another useful source of information, USDA NRCS’ *Engineering Field Handbook, Chapter 18* (USDA-NRCS, 1992), contains information about locating and selecting plant species (e.g., availability, size, tolerance to deposition, flooding, drought, and salt), installation information, maintaining quality control, establishment period, and maintenance. The soil bioengineering chapter of the handbook is available at http://www.info.usda.gov/CED/ftp/CED/EFH-Ch18.pdf. For the Great Lakes, the USACE has identified 33 upland plant species that have the potential to effectively decrease surface erosion of shorelines resulting from wind action and runoff (Hall and Ludwig, 1975). Michigan Sea Grant has also published two useful guides for shorefront property owners that provide information on vegetation and its role in reducing Great Lakes shoreline erosion (Tainter, 1982; Michigan Sea Grant College Program, 1988).

The USDA Forest Service has published *A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization*, which provide information on how to successfully plan and implement a soil bioengineering project, including the application of soil bioengineering techniques. The guide also provides specific tips for using soil bioengineering techniques successfully and is available at http://www.fs.fed.us/publications/soil-bio-guide. USDA-NRCS's *Engineering Field Handbook, Chapter 18* (USDA-NRCS, 1992) also provides guidance for soil bioengineering that includes characteristics, principles, design, and construction techniques of soil bioengineering. The chapter is national in scope and should be supplemented with regional and local information. Experts should also be consulted for planning and design of systems.

A good understanding of current and projected flooding is necessary for designing appropriately restored plant communities in the floodplain (FISRWG, 1998). Assessing critical flow is crucial and would include consideration of the magnitude, frequency, and duration of the bankfull and overbank flows. This information is key to decide which plants and materials can be successfully established. For example, a live fascine (described below) can withstand a velocity of 6 to 8 ft/sec, while one-inch gravel can withstand a velocity of 2.5 to 5 ft/sec (Fischenich, 2001).

Soil bioengineering provides an array of practices that are effective for both prevention and mitigation of NPS problems. This applied technology combines mechanical, biological, and ecological principles to construct protective systems that prevent slope failure and erosion. Adapted types of woody vegetation (shrubs and trees) are initially installed as key structural components, in specified configurations, to offer immediate soil protection and reinforcement. Soil bioengineering systems normally use cut, unrooted plant parts in the form of branches or rooted plants. As the systems establish themselves, resistance to sliding or shear displacement increases in streambanks and upland slopes (Gray and Leiser, 1989; Porter, 1992).

Specific nonstructural practices include (USDA-NRCS, 1992):

- Marsh creation and restoration
- Live staking
- Live fascines
- Brush layering
- Brush mattressing
- Branch packing
- Coconut fiber roll
- Dormant post plantings
- Tree revetments

Marsh Creation and Restoration

Marsh creation and restoration is a useful vegetative technique that can address problems with erosion of shorelines. Marsh plants perform two functions in controlling shore erosion (Knutson, 1988). First, their exposed stems 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. Second, marsh plants 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. Suitable fill material may be placed in the intertidal zone to create a wetlands planting terrace of sufficient width (at least 18 to 25 feet) if such a terrace does not already exist at the project site. 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.

Case Study: Galilee Salt Marsh Restoration

The coastal features of southern Rhode Island provide a variety of special habitats. The Galilee Bird Sanctuary is a 128-acre coastal wetland complex owned and managed by the Rhode Island Department of Environmental Management (RIDEM), Division of Fish and Wildlife. Unfortunately, much of the Galilee Salt Marsh has faced many challenges in its history. During the 1950s, unconfined dredge materials from the Port of Galilee were deposited over portions of the western side of the salt marsh where the Galilee Bird Sanctuary is located. These materials filled in a tidal channel and significantly altered the natural hydrology of the marsh.

Following a hurricane in 1954, the State Division of Public Works constructed the Galilee Escape Road to ensure that residents of Great Island would not be trapped by floods. The new road fragmented the previously continuous salt marsh and eliminated about 7 acres of marsh habitat. Changes in hydrology included restriction of tidal flushing, which transformed the once-productive salt marsh into dense thickets of invasive *Phragmites* and shrubs, and lead to reduction of natural coastal wetland habitats for migratory waterfowl, shorebirds, fish, and shellfish. Prior to the beginning of the restoration project, fewer than 20 aces of salt mash and open water existed in the sanctuary and only nine or so of those acres were vegetated salt marsh supported by tidal flow.

A number of partners, including the Rhode Island Department of Transportation, U.S. Army Corp of Engineers, Ducks Unlimited, U.S. Fish and Wildlife Service, RIDEM Fish and Wildlife, and other agencies, under the auspices of the Coastal America Program, participated in the Galilee Salt Marsh Restoration Project. Clean Water Act Section 319 funding contributed to the restoration efforts with a $64,300 grant to replace the undersized culverts and install self-regulating sluice and tide gates. The gates operate using a system of floats and balances that are precisely calibrated to close when water reaches a preset level.

Restoration of approximately 84 acres of salt marsh habitats and 14 acres of tidal creeks and ponds was completed and dedicated in October 1997. By the end of the 1999 growing season, *Phragmites* had been reduced by 68 percent. Positive effects on fish and wildlife populations have been noted. Finfish began to recolonized the tidal creeks within days following opening of the tide gates and waterfowl (duck and geese), including the American black duck, have use the restored marsh for nesting and feeding and during migration. Complete restoration is expected to take 10 years or more. The project has been an enormous success, and the salt marsh has been designated a bird sanctuary. The project is an excellent demonstration of collaboration among various branches of government.

Sources:
RIDEM. 1997. *DEM, ARMY Corps Hold Galilee Salt Marsh Restoration Ceremony*. Rhode Island Department of Environmental Management Press Release. http://www.state.ri.us/dem/news/1997/pr/1105971.htm. Accessed March 2004.

USEPA. 2002. *Galilee Salt Marsh Restoration: Undersized Culverts Replaced with Self-Regulating Gates*. U.S. Environmental Protection Agency, Section 319 Success Stories, Vol. III. http://www.epa.gov/owow/nps/Section319III/RI.htm. Accessed June 2003.

Live Staking

Live staking (Figure 3.2) is appropriate for relatively uncomplicated site conditions when construction time is limited. It can also be used to stabilize intervening area between other soil bioengineering techniques, such as live fascines (USDA-NRCS, 1992). Live staking involves the insertion and tamping of live, rootable vegetative cuttings into the ground. If correctly prepared and placed, the live stake will root and grow. A system of stakes creates a living root mat that stabilizes the soil by reinforcing and binding soil particles together and by extracting excess soil moisture. Stakes are generally 1 to 2 inches in diameter and 2 to 3 feet long. Specific site requirements and available cutting source will determine size. 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. Most willow species are ideal for live staking because they root rapidly and begin to dry out a slope soon after installation. Sycamore and cottonwood are also species commonly used for live staking. This is an appropriate technique for repair of small earth slips and slumps that are frequently wet. 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).

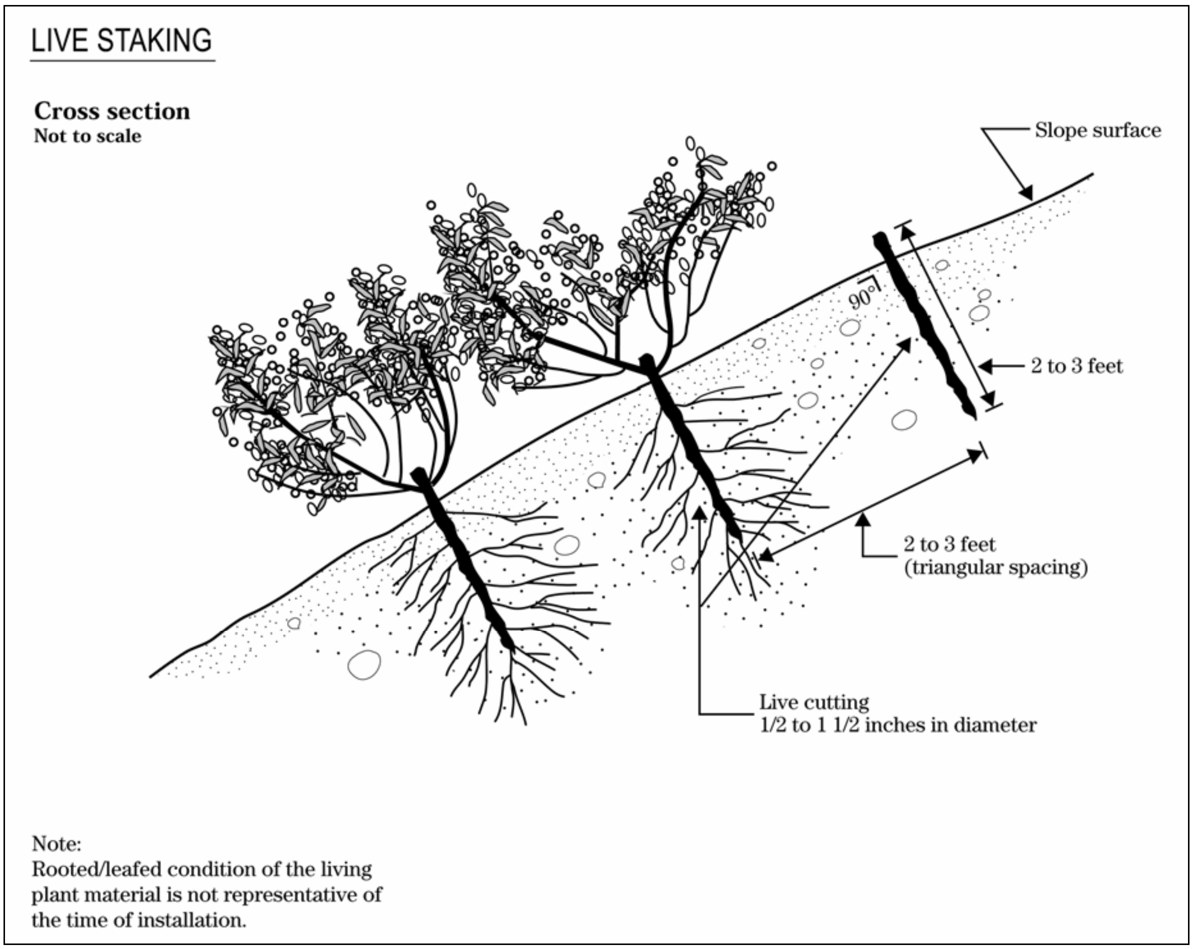


Figure 3.2 Live Staking (Source: USDA-NRCS, 1992)

Live Fascines

Live fascines are long bundles of branch cuttings bound together in a cylindrical structure (Figure 3.3). They 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. The cuttings (0.5 to 1.5 inches in diameter) form live fascine bundles that vary in length from 5 to 10 feet or longer, depending on site conditions and handling limitations. Completed bundles should be 6 to 8 inches in diameter. 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.

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*), at http://el.erdc.usace.army.mil/elpubs/pdf/sr31.pdf.

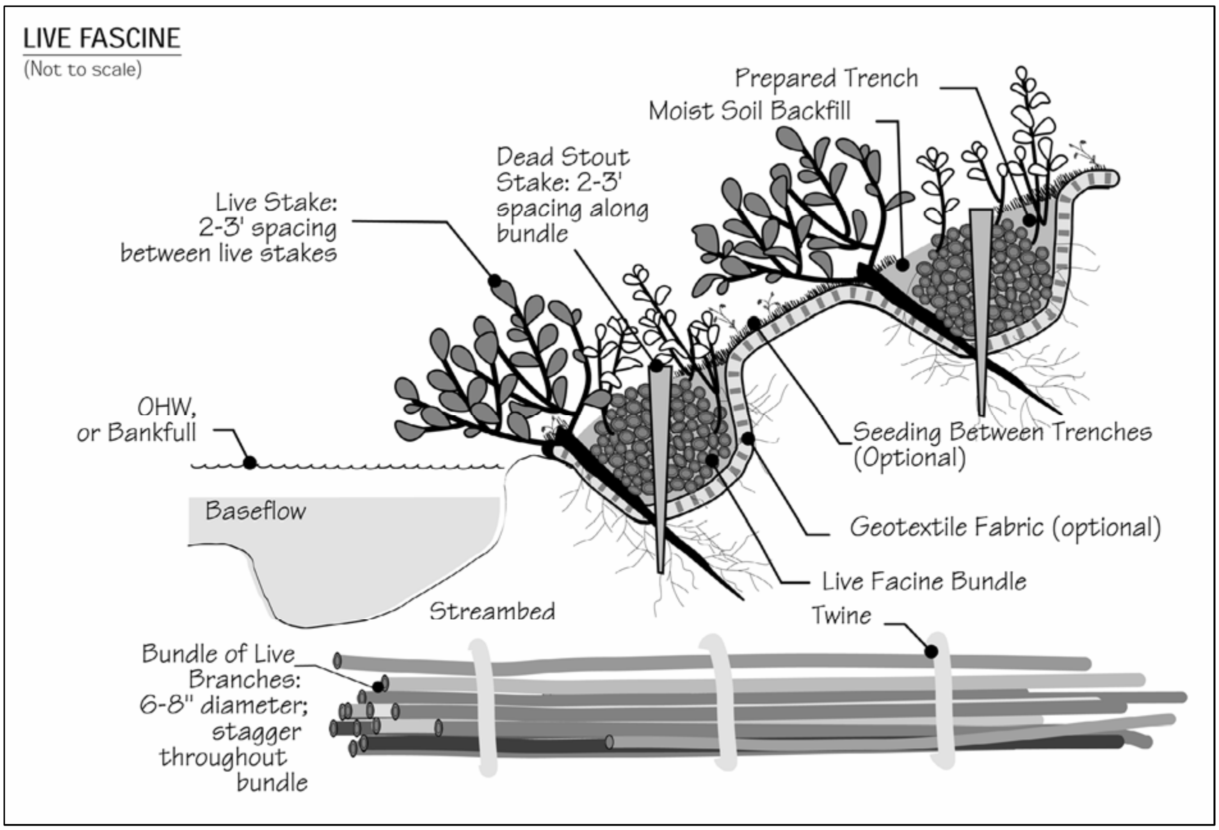


Figure 3.3 Live Fascine (Source: USDA-FS, 2002)

Note: OHW (Ordinary High Water) is the mark along a streambank where the waters are common and usual. This mark is generally recognized by the difference in the character of the vegetation above and below the mark or the absence of vegetation below the mark (USDA-FS, 2002).

Case Study: Red River Basin Riparian Project: Turtle River Site Passes the Test

Initiated in 1994, the Red River Basin Riparian Project seeks to restore degraded riparian corridors in the Red River Basin in North Dakota, caused by activities such as overgrazing, intensive agriculture, and indiscriminate logging. According to estimates, more than 50 percent of the original forest cover in many watersheds in eastern North Dakota has been cleared for agricultural use. An advisory committee with representatives from several state and federal agencies advises the project on behalf of the project's sponsor, the Red River Resource Conservation and Development Council. Healthy riparian corridors offer benefits for water quality, as well as flood damage reduction and wildlife habitat. The project sponsors' original goal was to establish demonstration sites in the Red River Basin, restoring at least 100 river miles over 5-years.

At one demonstration site, the Turtle River site, the lack of woody vegetation had left the streambank vulnerable to severe erosion. In addition, groundwater seeps above the baseflow elevation of the river were leading to erosion. Between 1978 and 1995, the river migrated approximately 3.5 feet per year to the east until it was only 80 feet from the county road. When the bioengineering project was initiated 1995, the site had a vertical bank about 14 feet high.

In 1995, efforts were made to stabilize the bank and stop further migration toward the road using multiple bioengineering techniques. The first step was to create a stable slope for the vegetation. The 14-foot vertical bank was reshaped to a 3:1 slope, using the waste from the top as fill at the toe. Riprap, willow fascines, a brush mattress, and grasses and shrubs were installed along the bank to aid in the revegetation process.

The Natural Resources Conservation Service demonstrated the implementation of several bioengineering techniques during a workshop (left). Willows were planted along the restoration site to provide long-term stability (right).

Although some maintenance was required each spring in 1996 and 1997, the project has survived spring floods and a 17-inch rainstorm in July 2000. Red River Riparian Projects continue to lessen erosion in demonstration sites in North Dakota.

In North Dakota riparian areas are essential factors in the long-term protection and enhancement of the streams, rivers, and lakes. Well-managed riparian zones may provide optimum food and habitat for stream communities and serve as buffer strips for controlling nonpoint source pollution. Riparian buffers, when used as part of an integrated management system, can greatly benefit the quality of the state's surface waters.

Sources:

Kingerly, L. 1997. Bioengineering Used to Stabilize Streambank Site on Turtle River. *Quality Water: Newsletter of the North Dakota Nonpoint Source Pollution Task Force*. Vo. 8, No. 2. http://www.health.state.nd.us/rrbrp/reports/Bioengineering.pdf. Accessed March 2004.

Red River Basin Riparian Project. 2003. http://www.health.state.nd.us/rrbrp. Accessed March 2004.

USEPA. 2002. *Red River Basin Riparian Project: Turtle River Site Passes the Test*. U.S. Environmental Protection Agency, Section 319 Success Stories, Vol. III. http://www.epa.gov/owow/nps/Section319III/ND.htm. Accessed June 2003.

Brush Layering

Brush layering consists of placing live branch cuttings in small benches excavated into the slope (Figures 3.4 and 3.5). The width of the benches can range from 2 to 3 feet. These systems are recommended on slopes up to 2:1 in steepness and not to exceed 15 feet in vertical height. Branch cuttings should be 0.5 to 2 inches in diameter and be long enough to reach the back of the bench and still protrude from the bank. The portions of the brush that protrude from the slope face assist in retarding runoff and reducing surface erosion. Brush layering is somewhat similar to live fascine systems because both involve the cutting and placement of live branch cuttings on slopes. The two techniques differ principally in the orientation of the branches and the depth to which they are placed in the slope. In brush layering, the cuttings are oriented more or less perpendicular to the slope contour. In live fascine systems, the cuttings are oriented more or less parallel to the slope contour. The perpendicular orientation is more effective from the point of view of earth reinforcement and mass stability of the slope (USDA-NRCS, 1992). 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).

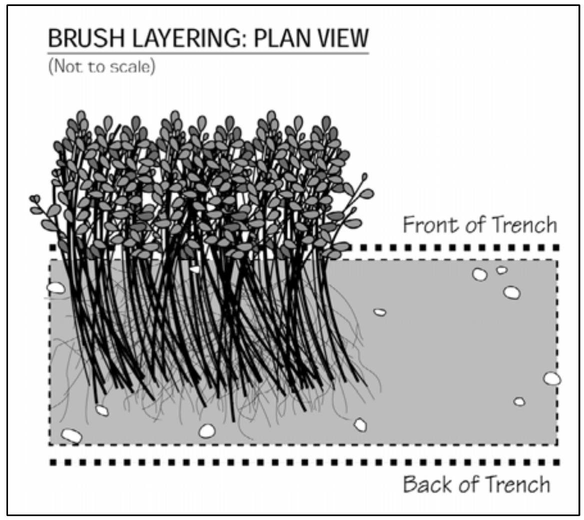


Figure 3.4 Brush Layering: Plan View (Source: USDA-FS, 2002)

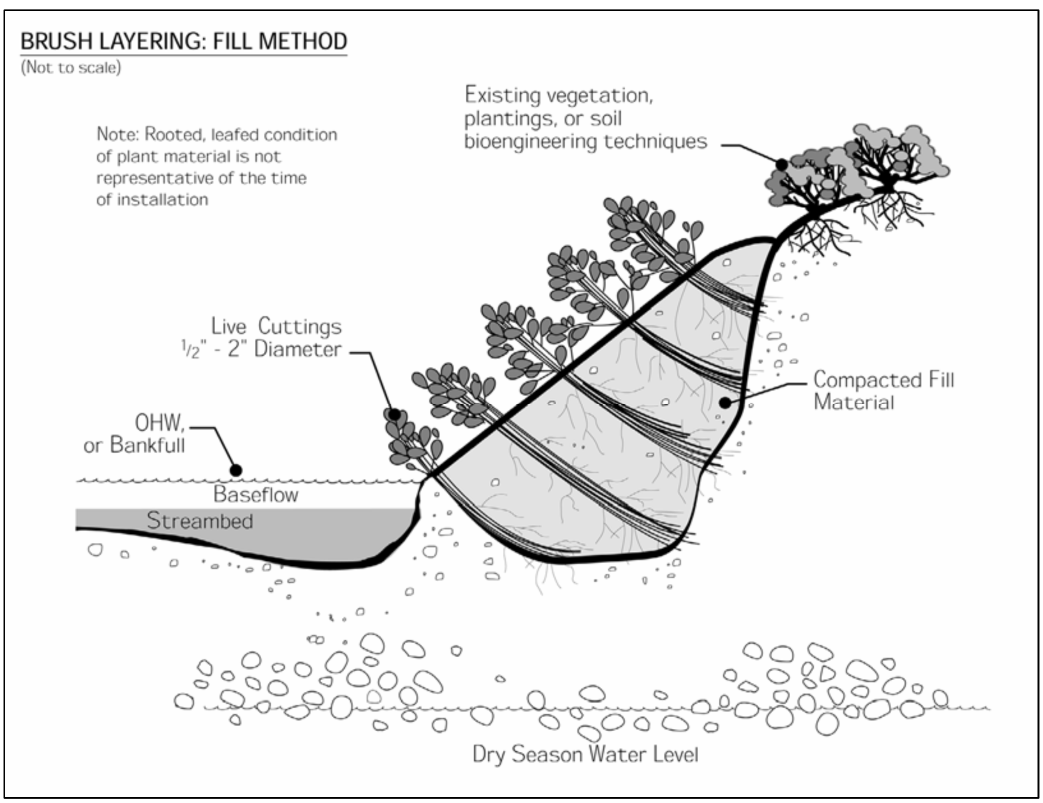


Figure 3.5 Brush Layering: Fill Method (Source: USDA-FS, 2002)

Brush Mattressing

Brush mattressing is commonly used in Europe for streambank protection (Figure 3.6). 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 1 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 may 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.

Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002). Under EMRRP, the U.S. Army Corps of Engineers has presented research on brush mattresses in a technical note (*Brush Mattresses for Streambank Erosion Control*), which is available at http://el.erdc.usace.army.mil/elpubs/pdf/sr23.pdf.

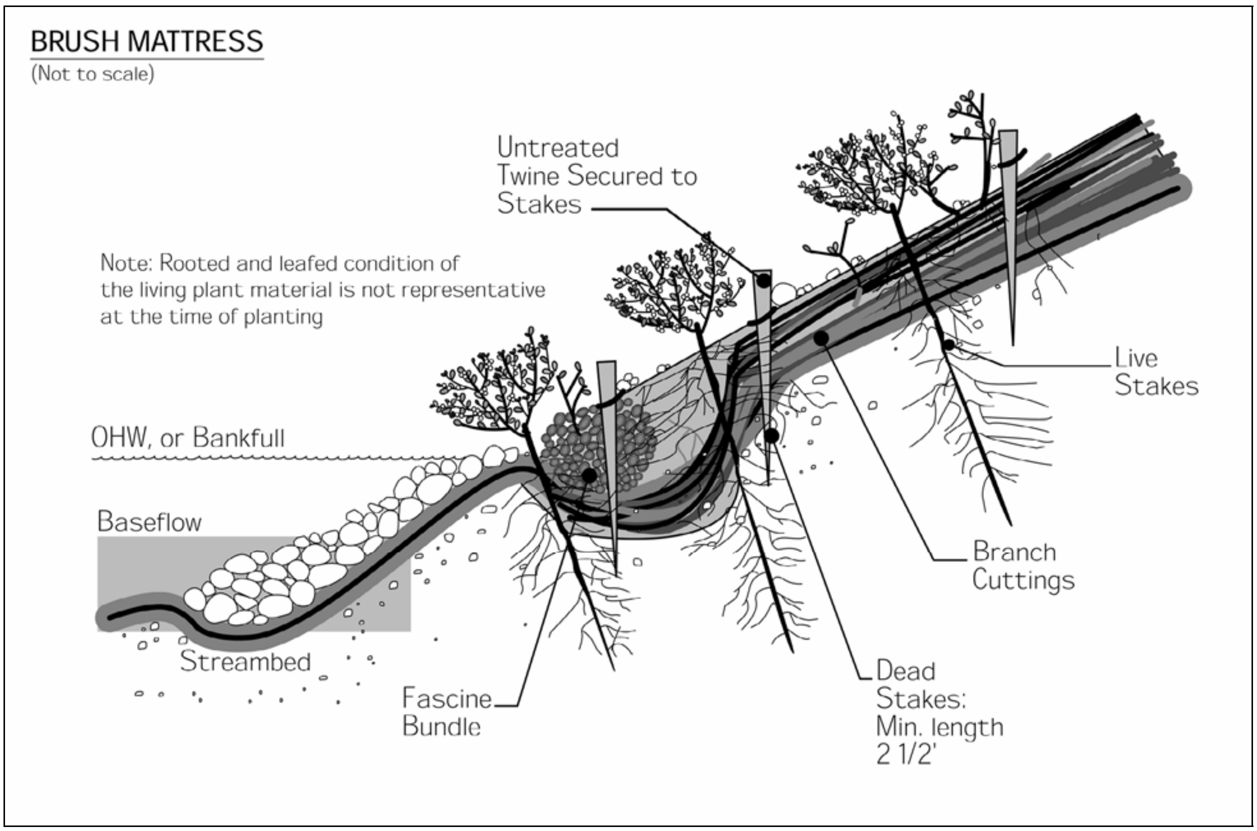


Figure 3.6 Brush Mattress (Source: USDA-FS, 2002)

Case Study: Middle Carson River Restoration: Using Bioengineering to Restore Unstable Banks

In 1997, the Carson River watershed (located in Nevada) experienced a 100-year flood event, which caused severe erosion and damage to riverbanks and the nearby riparian habitat along the Carson River. In response, the Middle Carson River Coordinated Resource Management Planning Committee (a group of ranchers and other concerned local citizens) began a project to restore the streambanks and riparian area. Due to the severity of the flood, and the lack of existing vegetation, the project used bioengineering in addition to hard structures to achieve bank stabilization and revegetation.

Restoring Streambanks with Bioengineering
In 1998, construction of five stream barbs to redirect flow away from the unstable banks began on the Glancy property near Dayton. Behind the structures, quiescent areas collect sediment and allow natural regeneration of native vegetation. For bioengineering, several vegetative treatments, including brush mattress layering, brush trenches, juniper revetments, willow clump planting, and seeding, were used. These treatments provide bank stability, reduce erosion, trap sediment, provide shading, encourage natural plant growth, and restore wildlife habitat.

Monitoring to Document Improvements
Long-term monitoring will evaluate the effectiveness of the best management practices used in this project. Aerial photography; annual survey of channel cross sections; monitoring of vegetation growth; analysis of soil characteristics to document particle size, erodibility, and sediment transport potential; and hydraulic modeling are part of the monitoring program. Public education also enhances community awareness and involvement.

Nine months after project's November 1998 completion, monitoring showed an average of 74 percent cover on all vegetative treatments, with about 35 percent regeneration of the willow clumps. A topographical survey indicated deposition of about 430 cubic yards of sediment between the stream barbs. Stream barbs appear to be functioning as designed to deflect higher stream flow away from the bank, such that the low-flow channel has moved away from the bendway.

As part of the public education component, bimonthly water quality monitoring of the Middle Carson River is conducted. River Wranglers, a volunteer group, has worked with local schools to educate students about river and lake ecology. Students measure dissolved oxygen, pH, and turbidity, and take macroinvertebrate samples in the field.

In July 2000, the Nevada Division of Environmental Protection awarded Kevin Piper and the Middle Carson River Coordinated Resource Management Group the Wendell McCurry Excellence in Water Quality Award. This award is to recognize individuals, firms, organizations, and governmental entities that have made significant contributions to improving the quality of Nevada's water resources. As of 2000, funding to date includes approximately $30,000 of Clean Water Act Section 319(h) funds and $30,000 in local matching funds. The strength of the Middle Carson group is their ability to work together to implement "on-the-ground" projects.

Sources:
Allen, H., C.J. Fischenich, and R. Seal. 2000. Bioengineering for erosion control and environmental improvements, Carson River, NV. In *Best Management Practices for Soft Engineering of Shorelines*, ed. A.D. Caulk, J.E. Gannon, J.R. Shaw, and J.H. Hartig. Greater Detroit American Heritage River Initiative.

Piper, K.L., J.C. Hoag, H.H. Allen, G. Durham, J.C. Fischenich, and R.O. Anderson. 2001. *Bioengineering as a tool for restoring ecological integrity to the Carson River.* ERDC TN-WRAP-01-05. U.S. Army Corps of Engineers, Wetlands Regulatory Assistance Program.

USEPA. 2002. *Middle Carson River Restoration Project: Bioengineering Used to Restore Unstable Banks*. U.S. Environmental Protection Agency, Section 319 Success Stories. http://www.epa.gov/owow/nps/Section319III/NV.htm. Accessed June 2003.

Branch Packing

Branch packing consists of alternating layers of live branch cuttings and compacted backfill to repair small, localized slumps and holes in slopes (Figure 3.7). Live branch cuttings may range from 0.5 to 2 inches in diameter. They should be long enough to touch the undisturbed soil at the back of the trench and extend slightly outward from the rebuilt slope face. Wooden stakes should be 5 to 8 feet long, depending on the depth of the slump or hole being repaired. These stakes should also be made from poles that are either 3 to 4 inches in diameter or 2 by 4 feet lumber. Live posts can be substituted. As plant tops begin to grow, the branch packing system becomes increasingly effective in retarding runoff and reducing surface erosion. Trapped sediment refills the localized slumps or holes, while roots spread throughout the backfill and surrounding earth to form a unified mass. Branch packing is not effective in slump areas greater than 4 feet deep or 5 feet wide (USDA-NRCS, 1992). 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).

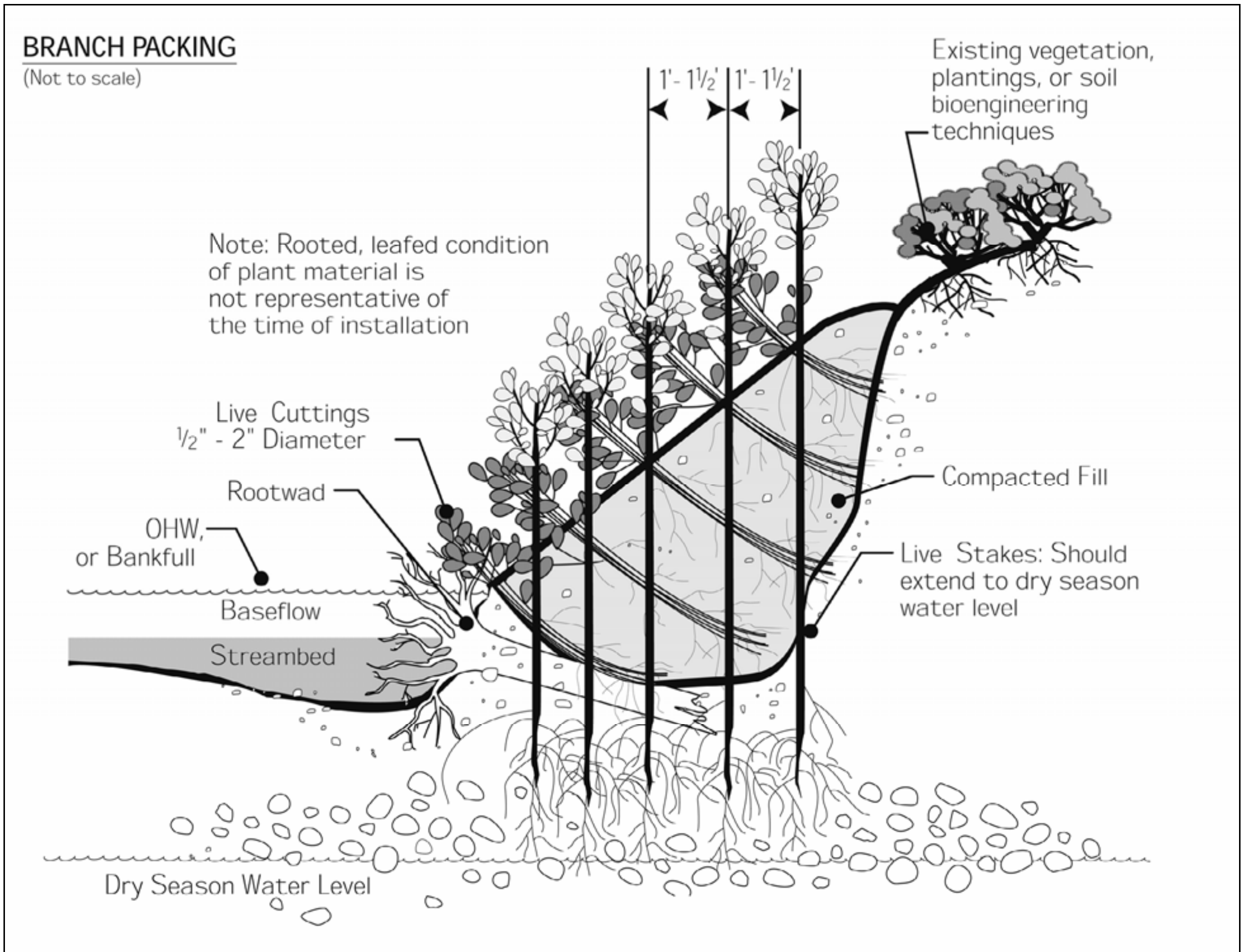


Figure 3.7 Branch Packing (Source: USDA-FS, 2002)

Coconut Fiber Roll

Figure 3.8 Coconut Fiber Roll Picture (Source: Montgomery Watson, 2001)

The coconut fiber roll technique consists of cylindrical structures composed of coconut husk fibers held together with twine woven from coconut material (Figures 3.8 and 3.9). It is typically manufactured in 12-inch diameters and lengths of 20 feet. This serves to protect slopes from erosion, trap sediment, and as a result, encourage plant growth within the fiber roll. The method is typically installed near the toe of the streambank with dormant cuttings and rooted plants inserted into holes cut into the fiber rolls. This provides a good substrate for promoting plant growth and is appropriate where short-term moderate toe stabilization is needed. Installation of this design requires minimal site disturbance and is ideal for sites that are especially sensitive to disturbance. A limitation of this system is that it cannot withstand high velocities or large ice buildup and it can be fairly expensive to construct. Coconut fiber rolls have an effective life of 6 to 10 years. In some locations, similar and abundant locally available materials, such as corn stalks, are being used instead of coconut materials (FISRWG, 1998).

Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002). Under EMRRP, the U.S. Army Corps of Engineers has presented research on coconut rolls in a technical note (*Coir Geotextile Roll and Wetland Plants for Streambank Erosion Control*), which is available at http://el.erdc.usace.army.mil/elpubs/pdf/sr04.pdf.

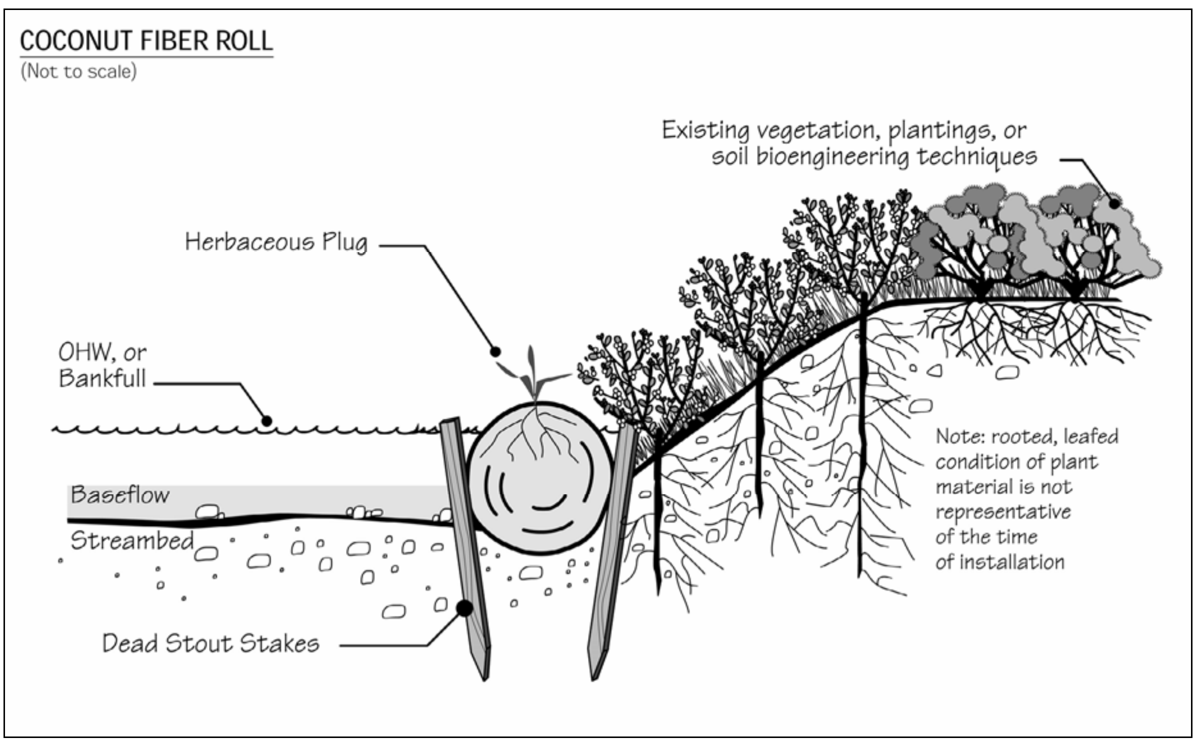


Figure 3.9 Coconut Fiber Roll (Source: USDA-FS, 2002)

Dormant Post Plantings

Dormant post plantings include planting of either cottonwood, willow, poplar or other sprouting species embedded vertically into streambanks to increase channel roughness, reduce flow velocities near the slope face, and trap sediment (Figure 3.10). Dormant posts are made up of large cuttings installed in streambanks in square or triangular patterns. Live posts should be 7 to 20 feet long and 3 to 5 inches in diameter. This method is effective for quickly establishing riparian vegetation particularly in arid regions. By decreasing near bank flow velocities, this design causes sediment deposition and reduces streambank erosion. This design is more resistant to erosion than live staking or similar designs that use smaller cuttings. Success of this design is most likely on streambanks that are not gravel dominated and where ice build up is not common. The exclusion of certain herbivores aids in the success of this design. This method should be combined with other soil bioengineering techniques to achieve a comprehensive streambank restoration design (FISRWG, 1998). Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002).

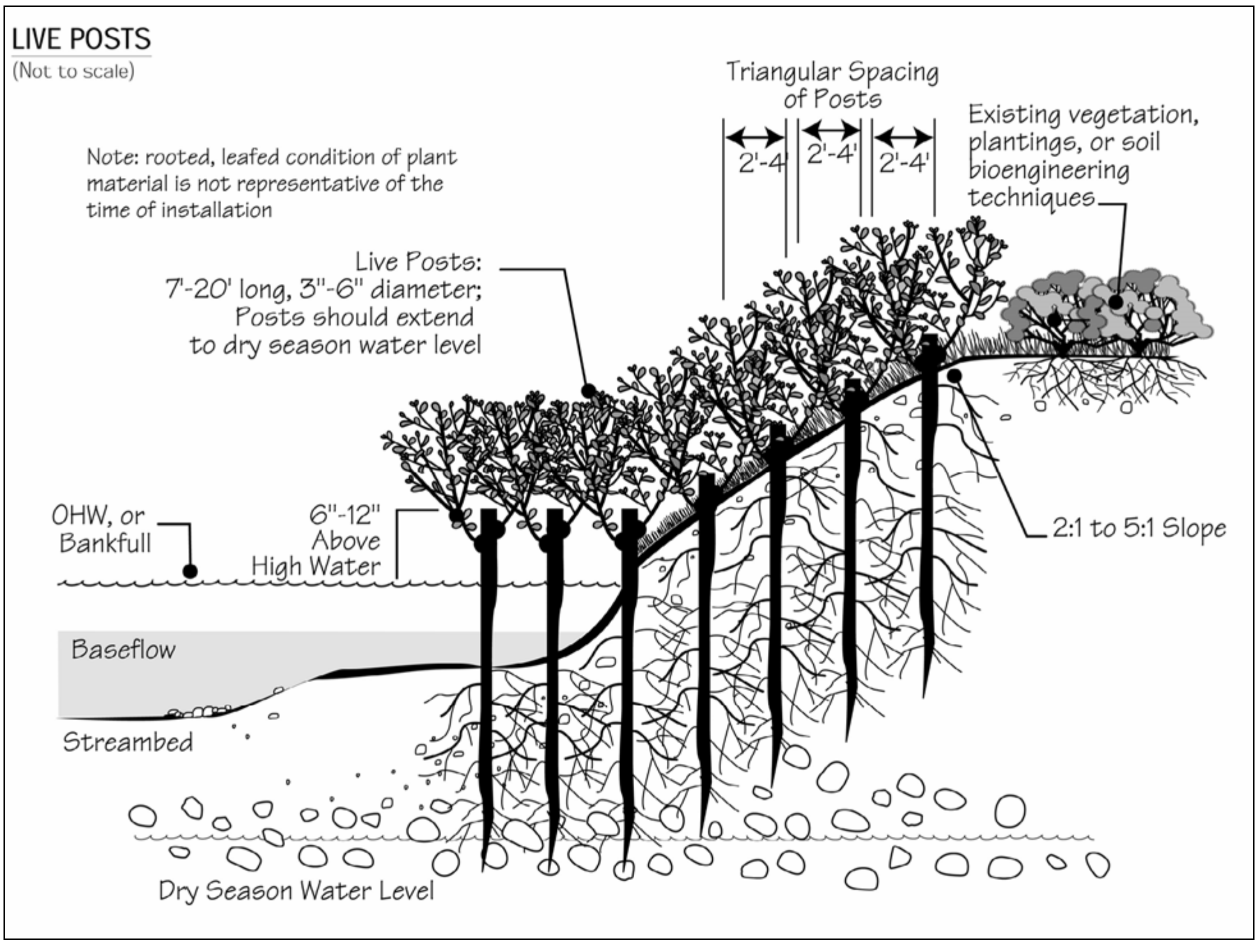


Figure 3.10 Live Posts (Source: USDA-FS, 2002)

Tree Revetments

Tree revetments consist of a row of interconnected trees anchored to the toe of the streambank or to the upper streambank (Figures 3.11 and 3.12). This serves to reduce flow velocities along eroding streambanks, trap sediment, and provide a substrate for plant establishment and erosion control. This design relies on the installation of an adequate anchoring system and is best suited for streambank heights under 12 feet and bankfull velocities under 6 feet per second. In addition, this structure should occupy no more than 15 percent of the channel at bankfull. Toe protection is needed to accompany this design if scour is anticipated and upper bank soil bioengineering techniques are recommended to ensure streamside regeneration. This design allows for the use of local materials if they are readily available. Decay resistant species are recommended for the logs to extend the life of the structure and thus the ability of vegetation to become established. Due to decomposition, these structures have a limited life and might require periodic replacement. It is considered beneficial that decomposition of the logs overtime allows the streambank to return to a natural state with protection provided by mature streambank vegetation. There is a potential for the logs to dislodge and these structures should not be located upstream of bridges or other structures sensitive to damage. Tree revetments are susceptible to damage by ice (FISRWG, 1998). Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002).

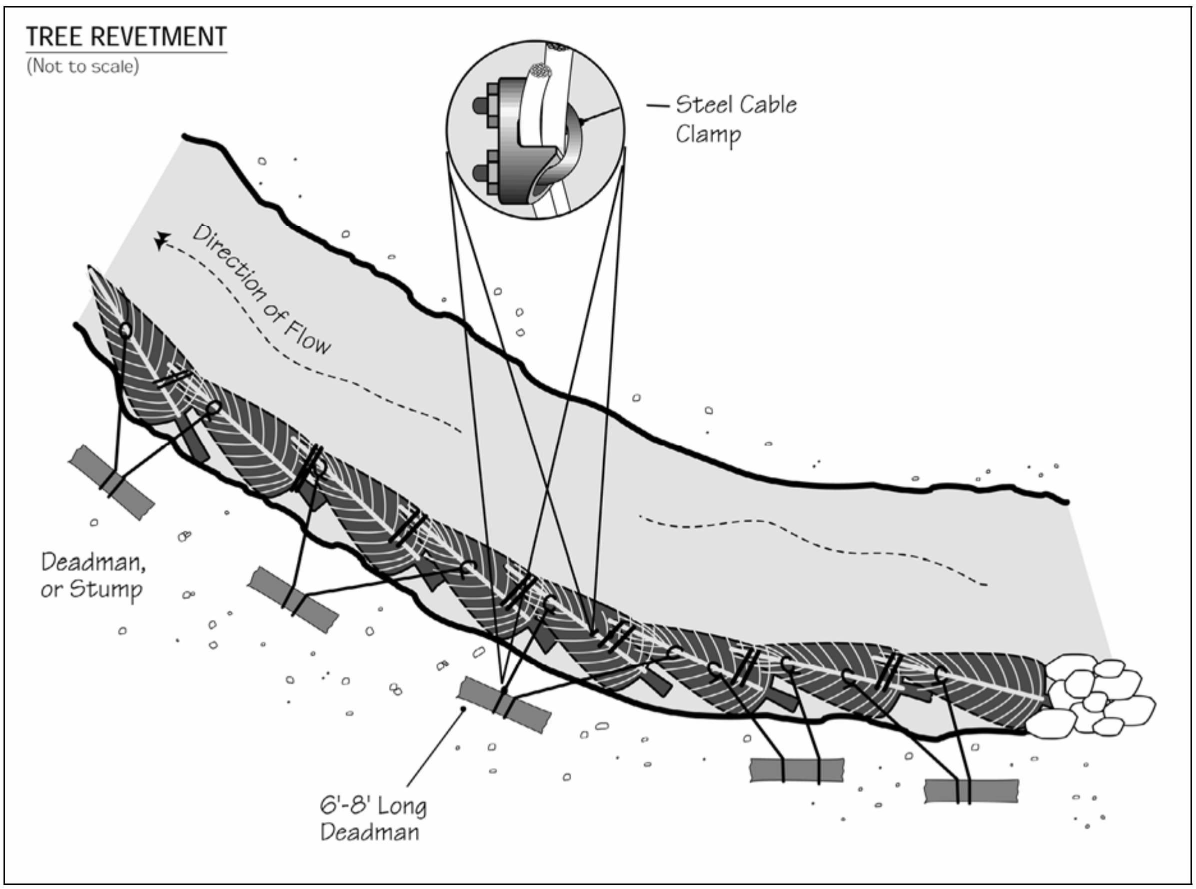


Figure 3.11 Tree Revetment (Source: USDA-FS, 2002)

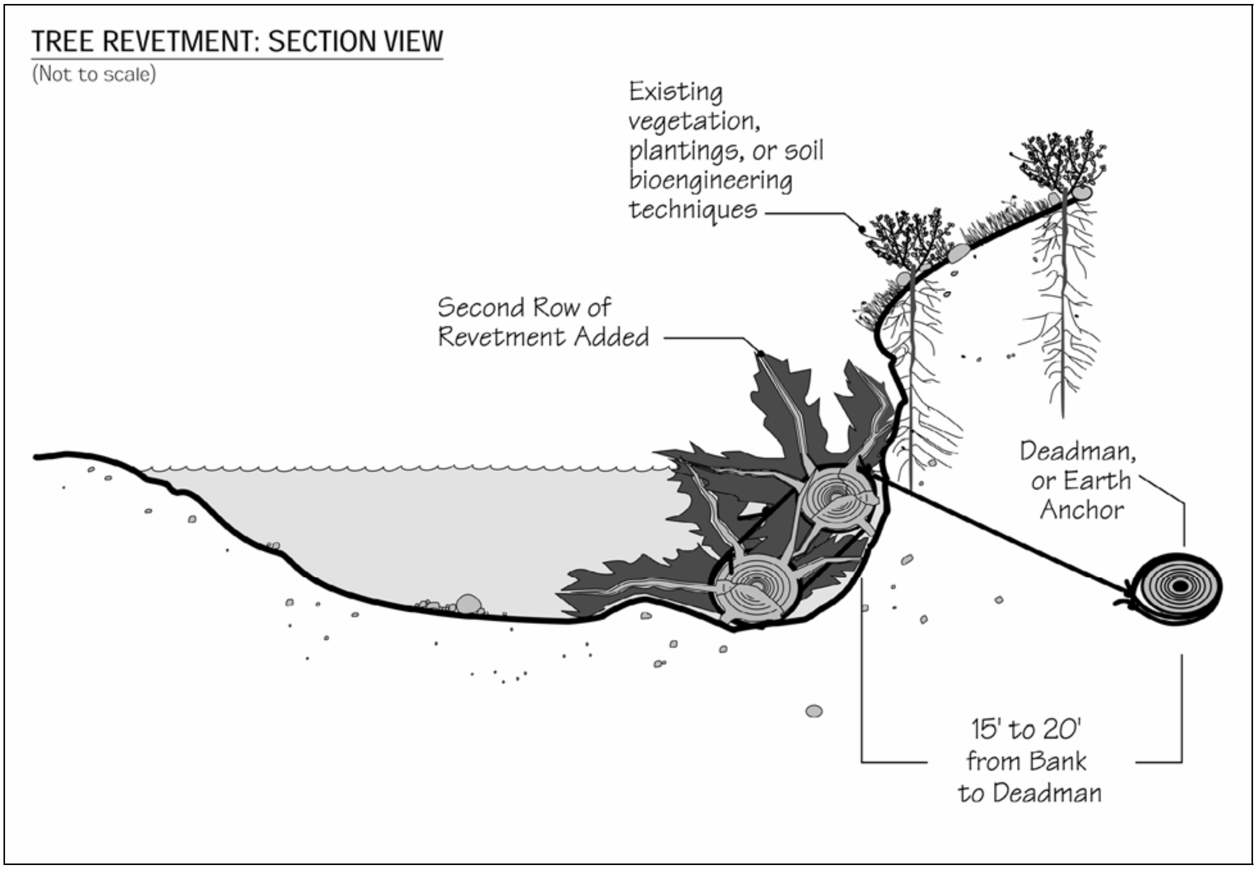


Figure 3.12 Tree Revetment: Section View (Source: USDA-FS, 2002)

Case Study: Streambank Stabilization Project: Tree Revetments Rescue Eroding Banks

Streambank erosion on Georgia's streams and rivers is a growing problem. Erosion has been particularly evident in the Broad River Watershed District of northeastern Georgia. Although it is much easier and more cost-effective to prevent erosion before it occurs than to restore streambanks after they are damaged, erosion already exists in many areas of Georgia. In the Broad River watershed, the Chestatee-Chattahoochee Resource Conservation and Development Council, through a Clean Water Act Section 319 grant from the Georgia Department of Natural Resources, Environmental Protection Division, has worked to combat these problems with "tree revetments." Through demonstration projects, the Council has shown landowners the positive effects of tree revetments on eroding streambanks. This technique is relatively inexpensive when compared to other streambank stabilization techniques used in the past. In addition, tree revetments are an environmentally-sound method of stabilization.

In a tree revetment, whole trees are cabled tightly together in giant bundles that are secured to the eroded streambank through an anchoring system of cables, in a shingled pattern, like the shingles on a roof. The technique is most useful when streambank heights are 6 feet or more, with a steep incline; revetments cannot be constructed on gradually sloped streambanks.

Tree revetments can greatly slow the stream current along an eroding bank, which decreases erosion and allows sediment to deposit in the revetment's tree branches. In addition to trapping sediment, the deposited materials form an excellent seedbed in which the seeds of riparian trees and other plants can sprout and grow. The resulting growth spreads roots throughout the revetment and into the streambank. Tree revetments also provide excellent habitat for birds, fish, and other wildlife.

The demonstration project was completed in March 2004, with a total of 16 tree revetment sites, plus additional BMPs throughout the Broad River watershed. The project has been deemed a success by many of the stakeholders, and landowners have been pleased with the results of the project. Monitoring has shown that stream erosion has been minimized, streambanks have been stabilized, vegetation has become established on streambanks, and the riparian habitats have been improved for wildlife.

Sources:
Personal communication with Jim Wren, Oconee River RC&D Council, Inc. April 28, 2004.

USEPA. 2002. *Broad River Streambank Stabilization Project: Tree Revetments Rescue Eroding Banks*. U.S. Environmental Protection Agency, Section 319 Success Stories, Vol. III. http://www.epa.gov/owow/nps/Section319III/GA.htm. Accessed June 2003.

Nonstructural techniques have been used extensively in Europe for streambank and shoreline protection and for slope stabilization. They have been practiced in the United States only to a limited extent primarily because other engineering options, such as the use of riprap, have been more commonly accepted practices (Allen and Klimas, 1986). With the costs of labor, materials, and energy rapidly rising, however, less costly alternatives of stabilization are being pursued as alternatives to engineering structures for controlling erosion of streambanks and shorelines.

Additionally, bioengineering has the advantage of providing food, cover, and instream and riparian habitat for fish and wildlife and results in a more aesthetically appealing environment than traditional engineering approaches (Allen and Klimas, 1986). Overall, site disturbance from the placement of soil bioengineering systems is limited due to the minimal site access required for materials and labor and the minimal disturbance caused by the installation of soil bioengineering systems (Gray and Sotir, 1996). Soil bioengineering tends to utilize native plants and materials that can be obtained from local stands of species. These plants are already well adapted to the climate and soil conditions of the area and thus have an increased chance of becoming established and surviving. The use of locally available plants also cuts the costs of a restoration project (Gray and Sotir, 1996). Thus, if a system is successful, it will blend in with the natural vegetation over time. Soil bioengineering techniques become more established and resistant to erosion and disturbance with time, as opposed to the traditional structural systems that often require reinforcement as time passes (Gray and Sotir, 1996). During the time period after installation, soil bioengineering systems are most vulnerable. As time passes the vegetation roots, the foliage leafs out, and the plants become well established. This causes the system to have increased resistance to erosion. The systems are often designed, however, to provide sufficient reinforcement directly after being installed (Gray and Sotir, 1996). This can make locating plant materials difficult (Gray and Sotir, 1996).

Additional benefits of using bioengineering methods include (USEPA, 2003c):

- Designed to be maintenance-free in the long run
- Enhances habitat not only by providing food and cover sources, but serving as a temperature control for aquatic and terrestrial animals
- If successful, can stabilize slopes effectively in a short period of time (e.g., one growing season)
- Self-repairing
- Filters overland runoff, increases infiltration, and attenuates flood peaks

The limitations of soil bioengineering include the need for skilled laborers and the difficultly of locating plant materials during the dormant season, which is the optimal time for installation. To properly establish a soil bioengineering planting, orientation, on-site training, and careful supervision are required. The costs still tend to be lower than traditional methods. Additionally, construction is usually performed during the dormant season when labor tends to be more available (Gray and Sotir, 1996). Another limitation, which is avoidable, is that thick vegetation may increase roughness values or increase friction and raise floodwater elevations. This should be taken into consideration during the planning stages of a project and prevented.

Structural Approaches

Soil bioengineering alone is not suitable in all instances. When considering an approach to streambank or shoreline stabilization, it is important to take several factors into account. For example, it is inappropriate to stabilize slopes with soil bioengineering systems in areas that would not support plant growth, such as those areas with soils that are toxic to plants, areas of high water velocity, or significant wave action (Gray and Sotir, 1996). Shores subject to wave erosion will usually require structures or beach nourishment to dampen wave or stream flow energy. In particular, the principles of soil bioengineering, discussed previously, will most likely be ineffective at controlling that portion of streambank or shoreline erosion caused by wave energy. However, soil bioengineering will typically be effective on the portion of the eroding streambank or shoreline located above the extent of the current or the zone of wave attack. Subsurface seepage and soil slumping may need to be prevented by dewatering the bank material. Steep banks may need to be reshaped to a gentler slope to accommodate the plant material (Hall and Ludwig, 1975). As an alternative, an integrated system that combines soil bioengineering measures with structural measures can be installed.

Properly designed and constructed shoreline and streambank erosion control structures are used in areas where higher water velocity or wave energy make biostabilization and marsh creation ineffective. There are many sources of information concerning the proper design and construction of shoreline and streambank erosion control structures. In addition to careful consideration of the engineering design, the proper planning for a shoreline or streambank protection project will include a thorough evaluation of the physical processes causing the erosion. To complete the analysis of physical factors, the following steps are suggested (Hobbs et al., 1981):

- Determine the limits of the shoreline reach
- Determine the rates and patterns of erosion and accretion and the active processes of erosion within the reach
- Determine, within the reach of the sites of erosion-induced sediment supply, the volumes of that sediment supply available for redistribution within the reach, as well as the volumes of that sediment supply lost from the reach
- Determine the direction of sediment transport and, if possible, estimation of the magnitude of the gross and net sediment transport rates
- Estimate factors such as ground-water seepage or surface water runoff that contribute to erosion

Some of the most widely accepted alternative engineering practices for streambank or shoreline erosion control are described below. These practices will have varying levels of effectiveness depending on the strength of waves, tides, streamflow, or currents at the project site. They will also have varying degrees of suitability at different sites and may have varying types of secondary impacts. One important impact that must always be considered is secondary effects, such as the transfer of wave or streamflow energy, which can cause erosion elsewhere, either offshore or alongshore. Finding a satisfactory balance between these three factors (effectiveness, suitability, and secondary impacts) is often the key to a successful streambank or shoreline erosion control project.

Fixed engineering structures are built to protect upland areas when resources are affected by erosive processes. Sound design practices for these structures are essential (Kraus and Pilkey, 1988). Not only are poorly designed structures typically unsuccessful in protecting the intended stretch of shoreline, but they also have a negative impact on other stretches of streambanks and shoreline as well.

Examples of structural approaches include:

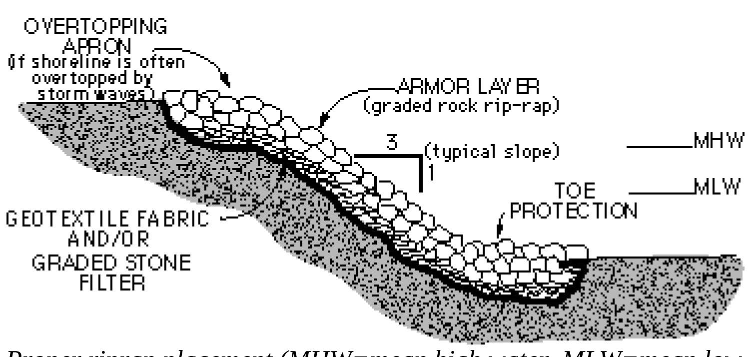
- Riprap
- Bulkheads and seawalls
- Revetment
- Groins
- Breakwaters
- Beach nourishment
- Toe protection
- Return walls
- Wing deflectors

Riprap

Riprap is a blanket of appropriately sized stones extending from the toe of the slope to a height needed for long term durability (Figures 3.13 and 3.14). (Joint plantings is an integrated version of the riprap method). This method is suitable where stream flow velocity is high or where there is a threat to life or property. This method can be expensive particularly if materials are not locally available. This method should be combined with soil bioengineering techniques, particularly revegetation efforts, to achieve a comprehensive streambank restoration design (FISRWG, 1998).

Figure 3.13 Riprap (Source: http://www.dnrec.state.de.us/dnrec2000/Divisions/Soil/dcmp/cdhydro.htm)

Placement of large rock, usually referred to as riprap, is the preferred and most common form of shore protection. Technical methods are available to determine rock size, placement geometry, and elevations to ensure the best protection. Specific county Soil and Water Conservation District (SWCD), the Minnesota Board of Water and Soil Resources (BWSR), and the federal Natural Resources Conservation Service (NRCS) can provide technical assistance.



Proper riprap placement (MHW=mean high water, MLW=mean low water).

Figure 3.14 Riprap Diagram
(Source: http://www.extension.umn.edu/distribution/naturalresources/components/DD6946g.html)

Bulkheads and Seawalls

Bulkheads (Figure 3.15) are primarily soil-retaining structures designed to also resist wave attack. Seawalls are principally structures designed to resist wave attack, but they also may retain some soil (USACE, 1984). Both bulkheads and seawalls may be built of many materials, including steel, timber, or aluminum sheet pile, gabions, or rubble-mound structures. Although bulkheads and seawalls protect the upland area against further erosion and land loss, they often create a local problem. Downward forces of water, produced by waves striking the wall, can produce a transfer of wave energy and rapidly remove sand from the wall (Pilkey and Wright, 1988). A stone apron is often necessary to prevent scouring and undermining. With vertical protective structures built from treated wood, there are also concerns about the leaching of chemicals used in the wood preservatives. Chromated copper arsenate (CCA), the most popular chemical used for treating the wood used in docks, pilings, and bulkheads, contains elements of chromium, copper, and arsenic, that are toxic above trace levels (CSWRCB, 2005; Kahler et al., 2000).

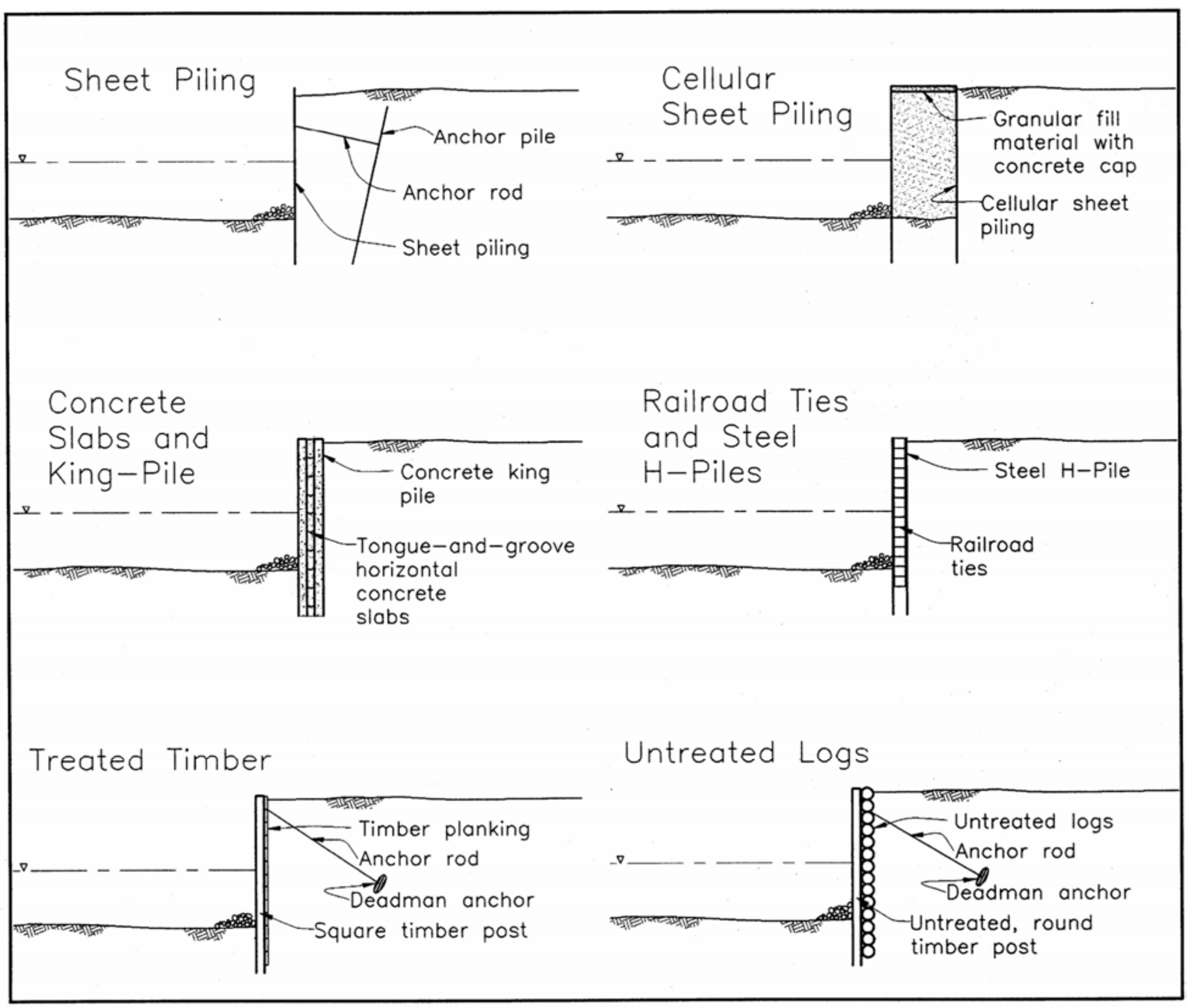


Figure 3.15 Typical Bulkhead Types (Source: USACE, 2003)

Revetment

A revetment (Figure 3.16) is a type of vertical protective structure used for shoreline protection. One revetment design contains several layers of randomly shaped and randomly placed stones, protected with several layers of selected armor units or quarry stone. The armor units in the cover layer should be placed in an orderly manner to obtain good wedging and interlocking between individual stones. The cover layer may also be constructed of specially shaped concrete units (USACE, 1984). Sometimes gabions (stone-filled wire baskets) or interlocking blocks of precast concrete are used in the construction of revetments. In addition to the surface layer of armor stone, gabions, or rigid blocks, successful revetment designs also include an underlying layer composed of either geotextile filter fabric and gravel or a crushed stone filter and bedding layer. This lower layer functions to redistribute hydrostatic uplift pressure caused by wave action in the foundation substrate. Precast cellular blocks, with openings to provide drainage and to allow vegetation to grow through the blocks, can be used in the construction of revetments to stabilize banks. Vegetation roots add additional strength to the bank. In situations where erosion can occur under the blocks, fabric filters can be used to prevent the erosion. Technical assistance should be obtained to properly match the filter and soil characteristics. Typically blocks

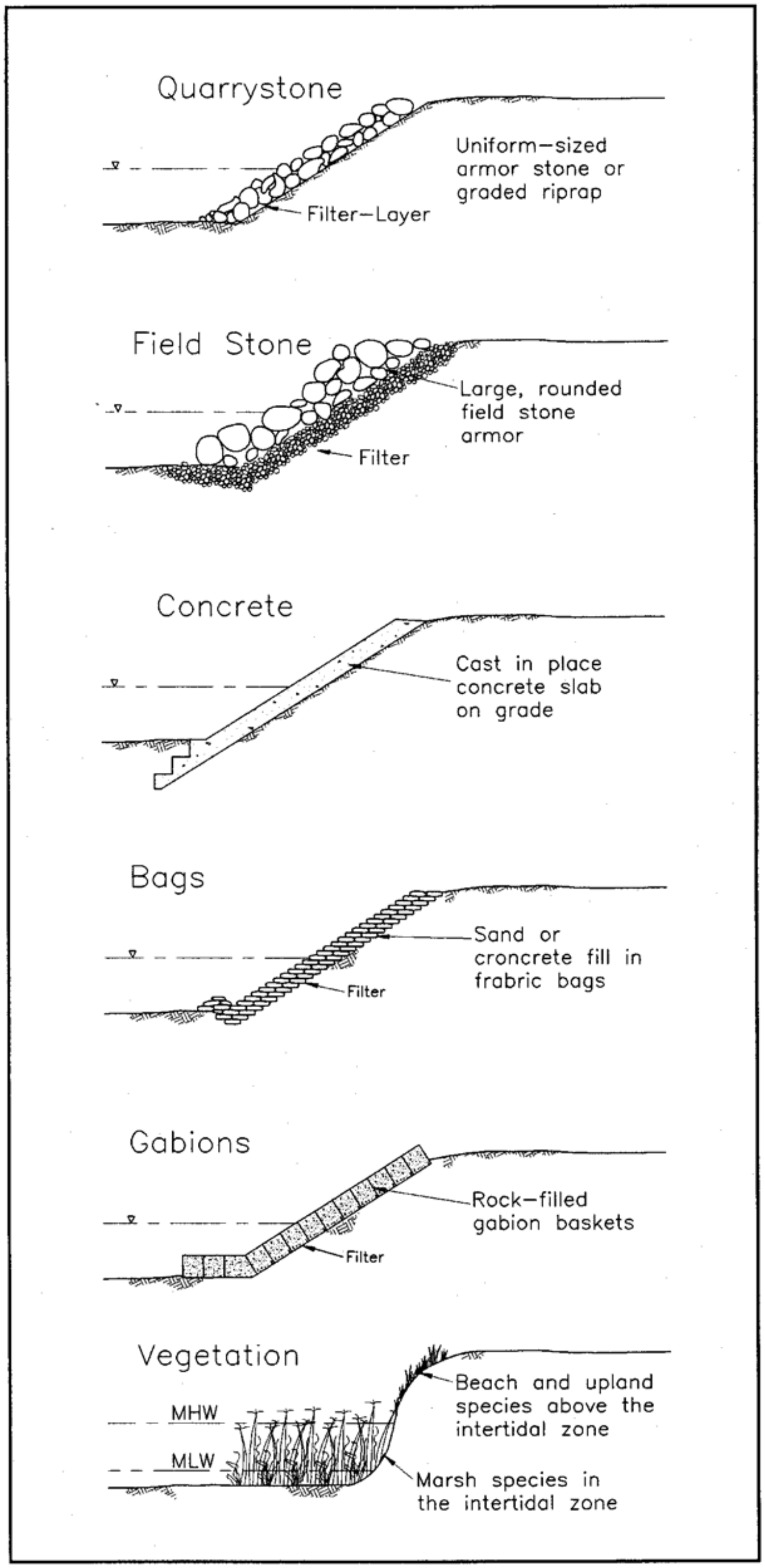


Figure 3.16 Revetment Alternatives (Source: USACE, 2003)

are hand placed when mechanical access to the bank is limited or costs need to be minimized. Cellular block revetments have the additional benefit of being flexible to conform to minor changes in the bank shape (USACE, 1983).

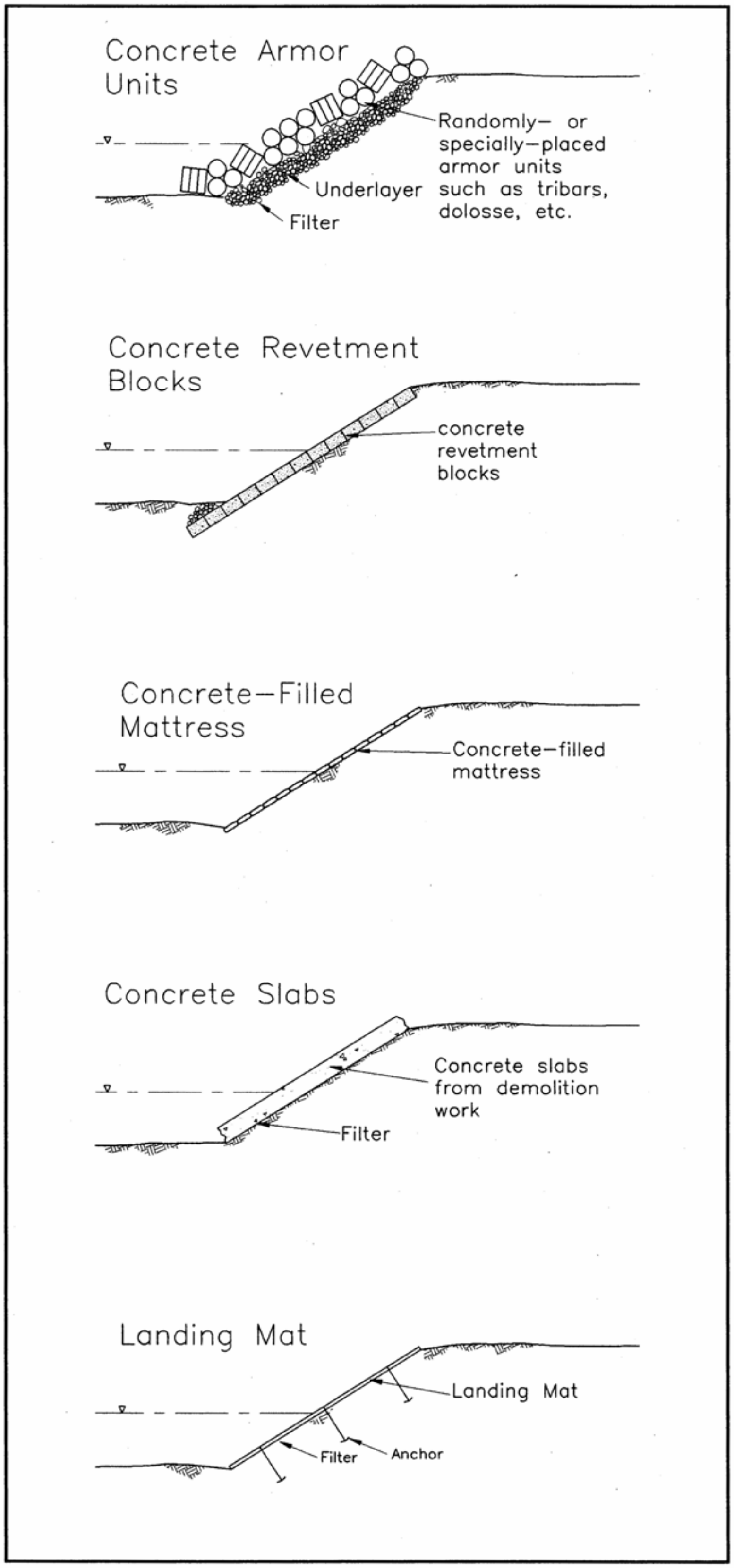


Figure 3.16 Revetment Alternatives, Continued (Source: USACE, 2003)

Groins

Groins are structures that are built perpendicular to the shore and extend into the water. Examples of possible planform shapes for groins are illustrated in Figure 3.17. They are generally constructed in series, referred to as a groin field, along the entire length of shore to be protected. Groins trap sand in littoral drift and halt its longshore movement along beaches. The sand beach trapped by each groin acts as a protective barrier that waves can attack and erode without damaging previously unprotected upland areas. Unless the groin field is artificially filled with sand from other sources, sand is trapped in each groin by interrupting the natural supply of sand moving along the shore in the natural littoral drift. This frequently results in an inadequate natural supply of sand to replace that which is carried away from beaches located farther along the shore in the direction of the littoral drift. If these “downdrift” beaches are kept starved of sand for sufficiently long periods of time, severe beach erosion in unprotected areas can result. As with bulkheads and revetments, the most durable materials used in the construction of groins are timber and stone. Less expensive techniques for building groins use sand- or concrete-filled bags or tires. It must be recognized that the use of lower-cost materials in the construction of bulkheads, revetments, or groins frequently results in less durability and reduced project life. Figure 3.18 illustrates transition from a groin field to a natural shoreline.

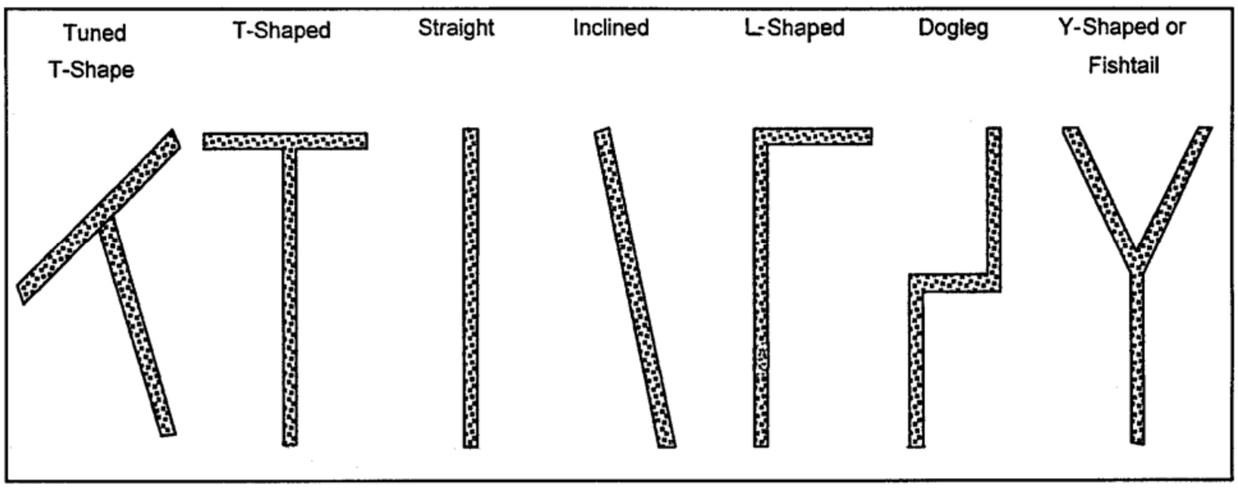


Figure 3.17 Possible Planform Shapes for Groins (Source; USACE, 2003)

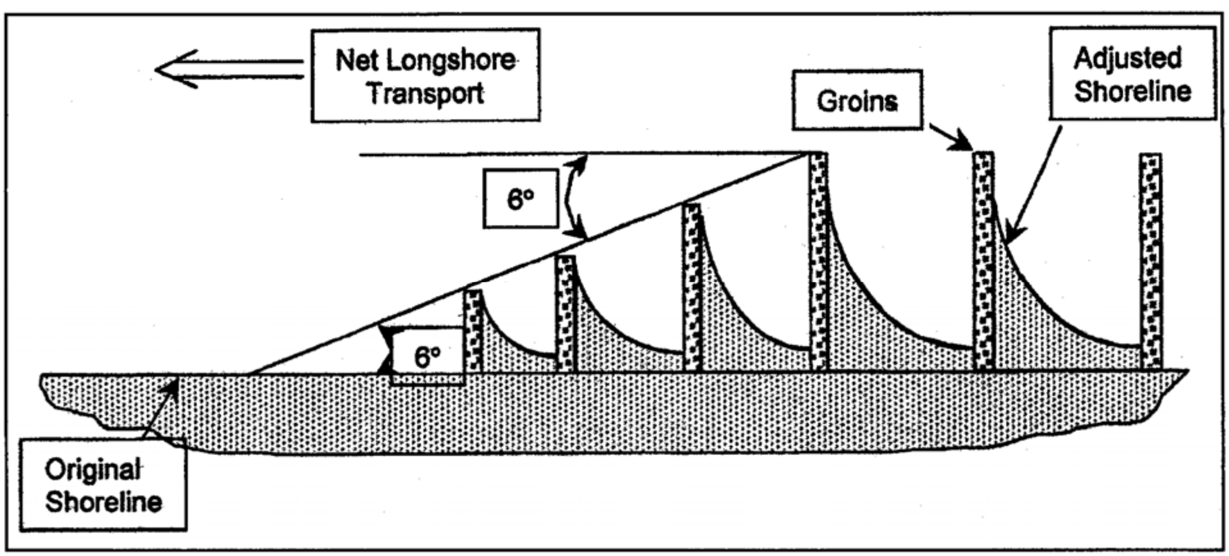


Figure 3.18 Transition from Groin Field to Natural Shoreline (Source: USACE, 2003)

Breakwaters

Figure 3.19 Breakwaters – View of Presque Isle, Pennsylvania (Source: USACE, 2003)

Breakwaters are wave energy barriers designed to protect the land or nearshore area behind them from the direct assault of waves. Breakwaters have traditionally been used only for harbor protection and navigational purposes; in recent years, however, designs of shore-parallel segmented breakwaters have been used for shore protection purposes (Fulford, 1985; USACE, 1990; Hardaway and Gunn, 1989; Hardaway and Gunn, 1991). Segmented breakwaters can be used to provide protection over longer sections of shoreline than is generally affordable through the use of bulkheads or revetments. Wave energy is able to pass through the breakwater gaps, allowing for the maintenance of some level of longshore sediment transport, as well as mixing and flushing of the sheltered waters behind the structures. The cost per foot of shore for the installation of segmented offshore breakwaters is generally competitive with the costs of stone revetments and bulkheads (Hardaway et al., 1991).

Figure 3.19 provides a view of breakwaters off the coast of Pennsylvania and Figure 3.20 illustrates single and multiple breakwaters.

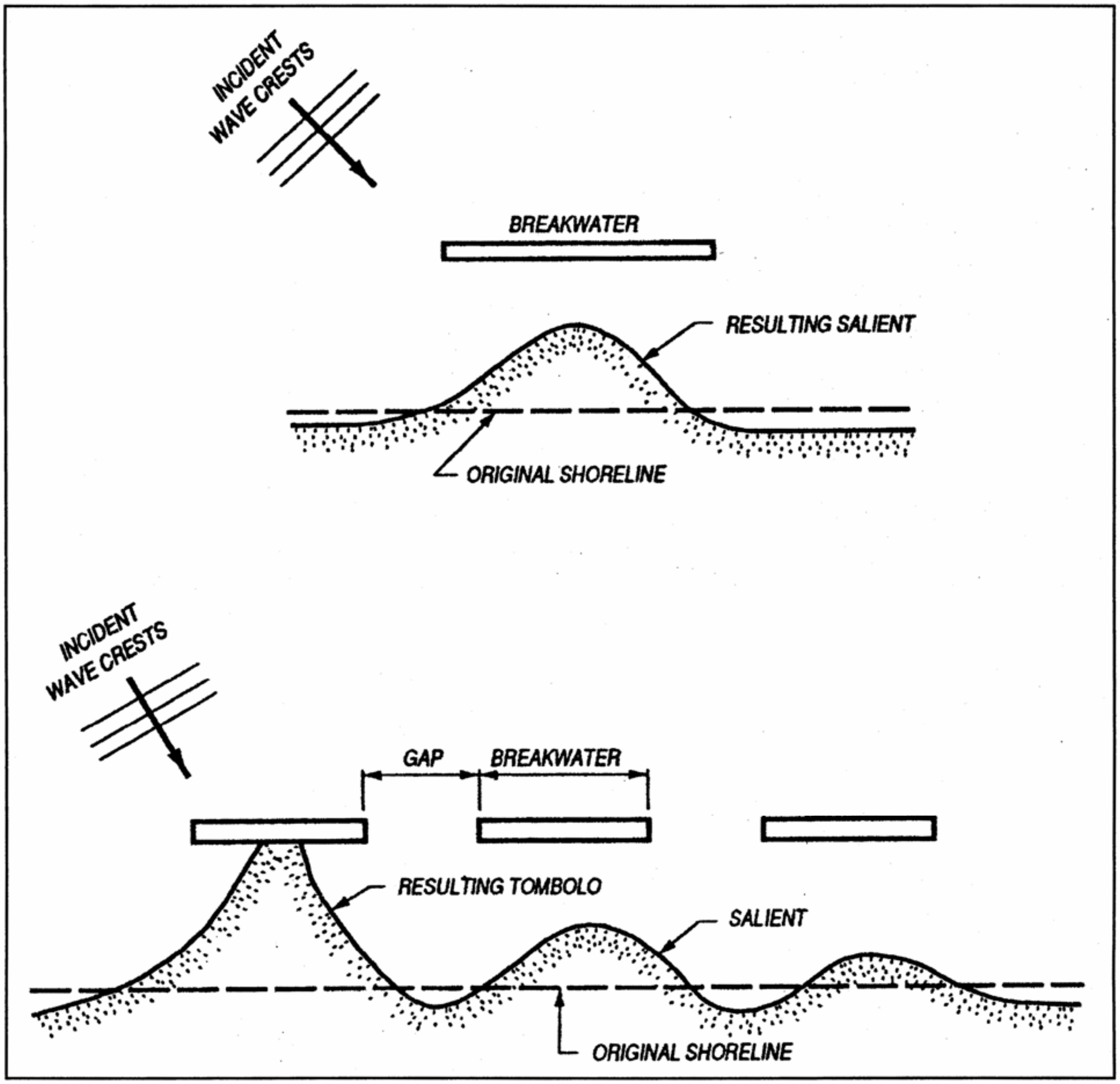


Figure 3.20 Single and Multiple Breakwaters (Source: USACE, 2003)

Beach Nourishment

The creation or nourishment of existing beaches provides protection to the eroding area and can also provide a riparian habitat function, particularly when portions of the finished project are planted with beach or dune grasses (Woodhouse, 1978). Beach nourishment (Figures 3.21 through 3.24) requires a readily available source of suitable fill material that can be effectively transported to the erosion site for reconstruction of the beach (Hobson, 1977). Dredging or pumping from offshore deposits is the method most frequently used to obtain fill material for beach nourishment. A second possibility is the mining of suitable sand from inland areas and overland hauling and dumping by trucks. To restore an eroded beach and stabilize it at the restored position, fill is placed directly along the eroded sector (USACE, 1984). In most cases, plans must be made to periodically obtain and place additional fill on the nourished beach to replace sand that is carried offshore into the zone of breaking waves or alongshore in littoral drift (Houston, 1991; Pilkey, 1992).

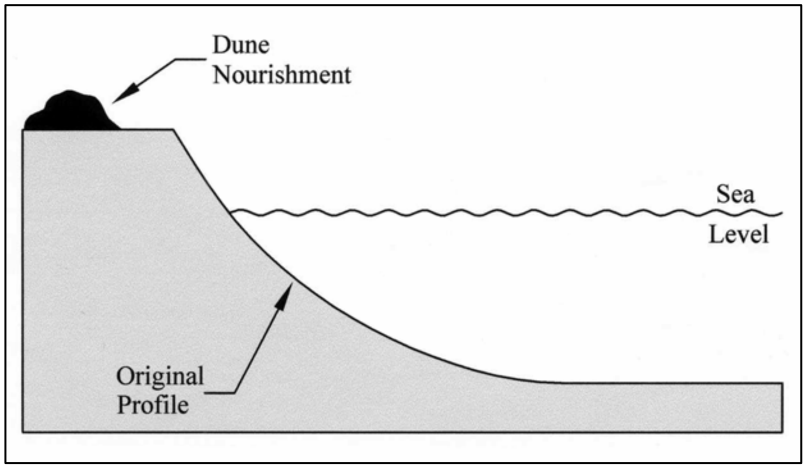


Figure 3.21 Dune Nourishment (Source: California Department of Boating and Waterways and State Coastal Conservancy, 2002)

One important task that should not be overlooked in the planning process for beach nourishment projects is the proper identification and assessment of the ecological and hydrodynamic effects of obtaining fill material from nearby submerged coastal areas. Removal of substantial amounts of bottom sediments in coastal areas can disrupt populations of fish, shellfish, and benthic organisms (Atlantic States Marine Fisheries Commission, 2002). Grain size analysis should be performed on sand from both the borrow area and the beach area to be nourished. Analysis of grain size should include both size and size distribution, and fill material should match both of these parameters (Stauble, 2005). Fill materials should also be analyzed for the presence of contaminants, and contaminated sediment should not be used (California Department of Boating and Waterways and State Coastal Conservancy, 2002). Turbidity levels in the overlying waters can also be raised to undesirable levels (EUCC, 1999). Certain areas

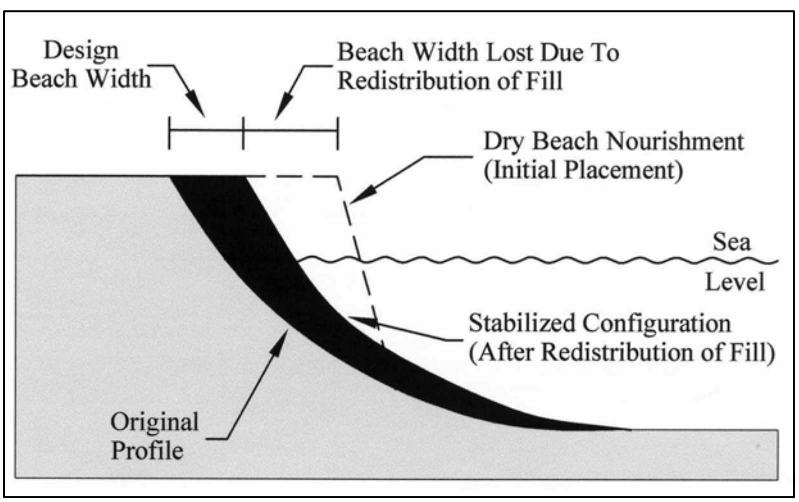


Figure 3.22 Dry Beach Nourishment (Source: California Department of Boating and Waterways and State Coastal Conservancy, 2002)

may have seasonal restrictions on obtaining fill from nearby submerged areas (TRB, 2001). Timing of nourishment activities is frequently a critical factor since the recreational demand for beach use frequently coincides with the best months for completing the beach nourishment. These may also be the worst months from the standpoint of impacts to aquatic life and the beach community such as turtles seeking nesting sites.

Design criteria should include proper methods for stabilizing the newly created beach and provisions for long-term monitoring of the project to document the stability of the newly created beach and the recovery of the riparian habitat and wildlife in the area.

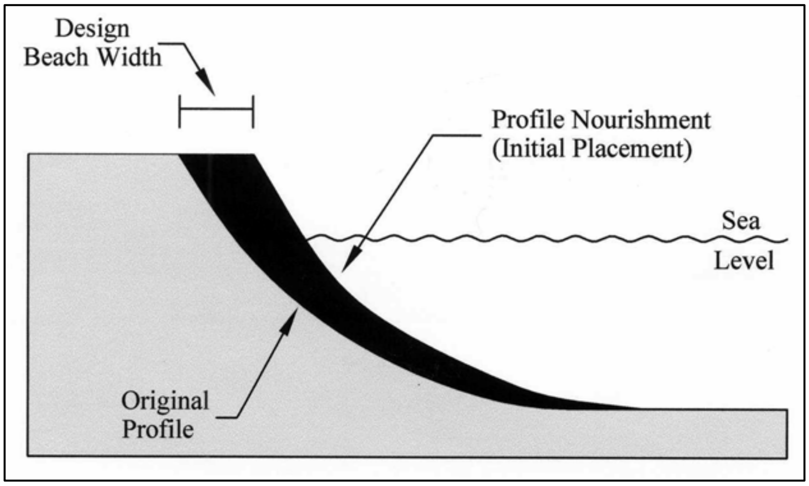


Figure 3.23 Profile Nourishment (Source: California Department of Boating and Waterways and State Coastal Conservancy, 2002)

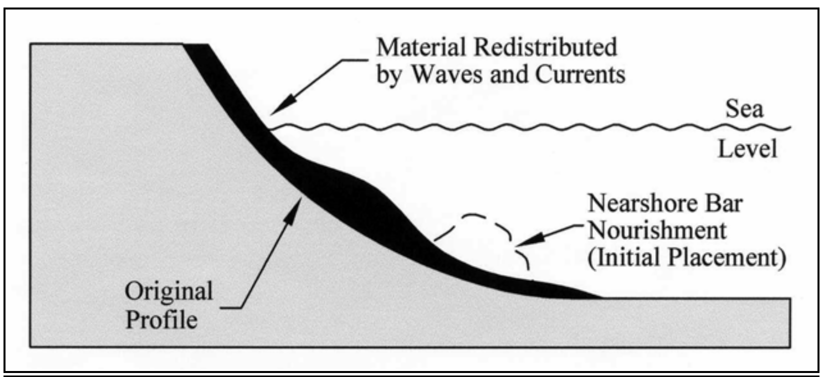


Figure 3.24 Nearshore Bar Nourishment (Source: California Department of Boating and Waterways and State Coastal Conservancy, 2002)

Toe Protection

A number of qualitative advantages are to be gained by providing toe protection for vertical bulkheads. Toe protection usually takes the form of a stone apron installed at the base of the vertical structure to reduce wave reflection and scour of bottom sediments during storms. The installation of rubble toe protection should include filter cloth and perhaps a bedding of small stone to reduce the possibility of rupture of the filter cloth. Ideally, the rubble should extend to an elevation such that waves will break on the rubble during storms.

Return Walls

> *In areas where existing protection methods are being flanked or are failing, implement properly designed and constructed shore erosion control methods such as returns or return walls, toe protection, and proper maintenance or total replacement.*

Whenever shorelines or streambanks are "hardened" through the installation of bulkheads, seawalls, or revetments, the design process must include consideration that waves and currents can continue to dislodge the substrate at both ends of the structure, resulting in very concentrated erosion and rapid loss of fastland. This process is called flanking. To prevent flanking, return walls should be provided at either end of a vertical protective structure and should extend landward for a horizontal distance consistent with the local erosion rate and the design life of the structure.

Wing Deflectors

Wing deflectors are structures that protrude from either streambank but do not extend entirely across a channel. The structures 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 alternative 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 may be susceptible to failure and should be constructed with the use a filter layer or geotextile fabric beneath the wing deflector structure (FISRWG, 1998).

Integrated Systems

The use of structural systems alone may raise concern because these systems lack vegetation, which can often be effective at stabilizing soils in most conditions. Additionally, vegetated systems can help to restore damaged habitat along shorelines and streambanks. Although there is little evidence to confirm this, in the past, some thought that vegetation could destabilize structures, such as stone revetments. However, integrated systems, which combine structural systems and vegetation, can be very effective in many settings where vegetation adds support and habitat to structural systems. An example of an integrated system is the use of stones for toe protection (structural) and soil bioengineering techniques (vegetative) for the upper banks.

Integrated slope protection designs that employ the traditional structural methods and the soil bioengineering techniques have proven to be more cost effective than either method independently. Where construction methods are labor-intensive and labor costs are reasonable, the combination of methods may be especially cost effective (Gray and Sotir, 1996).

Integrated systems include:

- Joint planting
- Live cribwalls
- Bank shaping and planning
- Vegetated gabions

- Rootwad revetments
- Vegetated geogrids
- Vegetated reinforced soil slope (VRSS)

Joint Planting

Joint planting (or vegetated riprap) involves tamping live cuttings of rootable plant material into soil between the joints or open spaces in rocks that have previously been placed on a slope (Figure 3.25). Alternatively, the cuttings can be tamped into place at the same time that rock is being placed on the slope face. 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. 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).

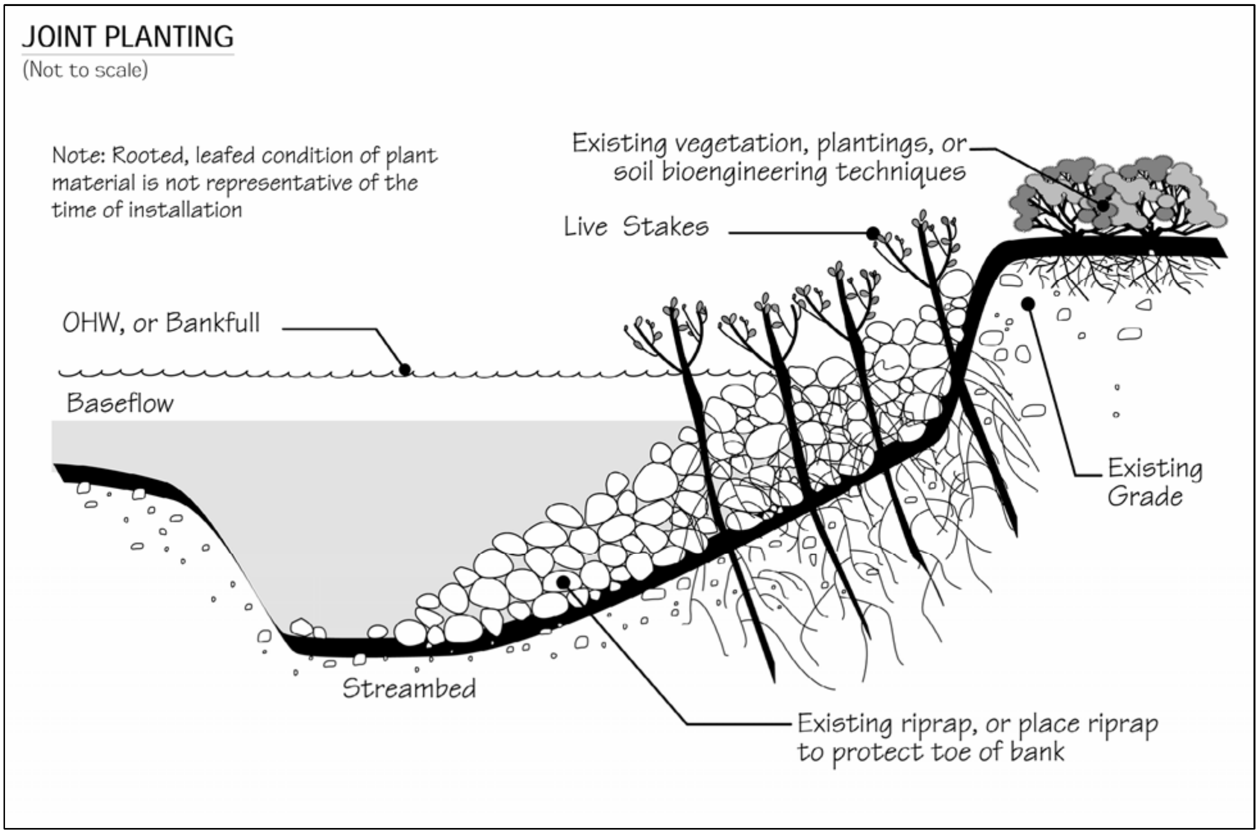


Figure 3.25 Joint Planting (Source: USDA-FS, 2002)

Live Cribwalls

A live cribwall is used to rebuild a bank in a nearly vertical setting. It consists of a hollow, box-like interlocking arrangement of untreated log or timber members (Figure 3.26). The structure is filled with suitable backfill material and layers of live branch cuttings, which root inside the crib structure and extend into the slope. Logs or untreated timbers should range from 4 to 6 inches in diameter. Lengths will vary with the size of the crib structure. Fill rock should be 6 inches in diameter. Live branch cuttings should be 0.5 to 2.5 inches in diameter and long enough to reach the back of the wooden crib structure. Once the live cuttings root and become established, the subsequent vegetation gradually takes over the structural functions of the wood members. Live cribwalls are appropriate where space is limited and at the base of a slope where a low wall may be required to stabilize the toe of the slope and to reduce its steepness. They are also appropriate above and below the water level where stable streambeds exist. They are not designed for or intended to resist large, lateral earth stress. 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).

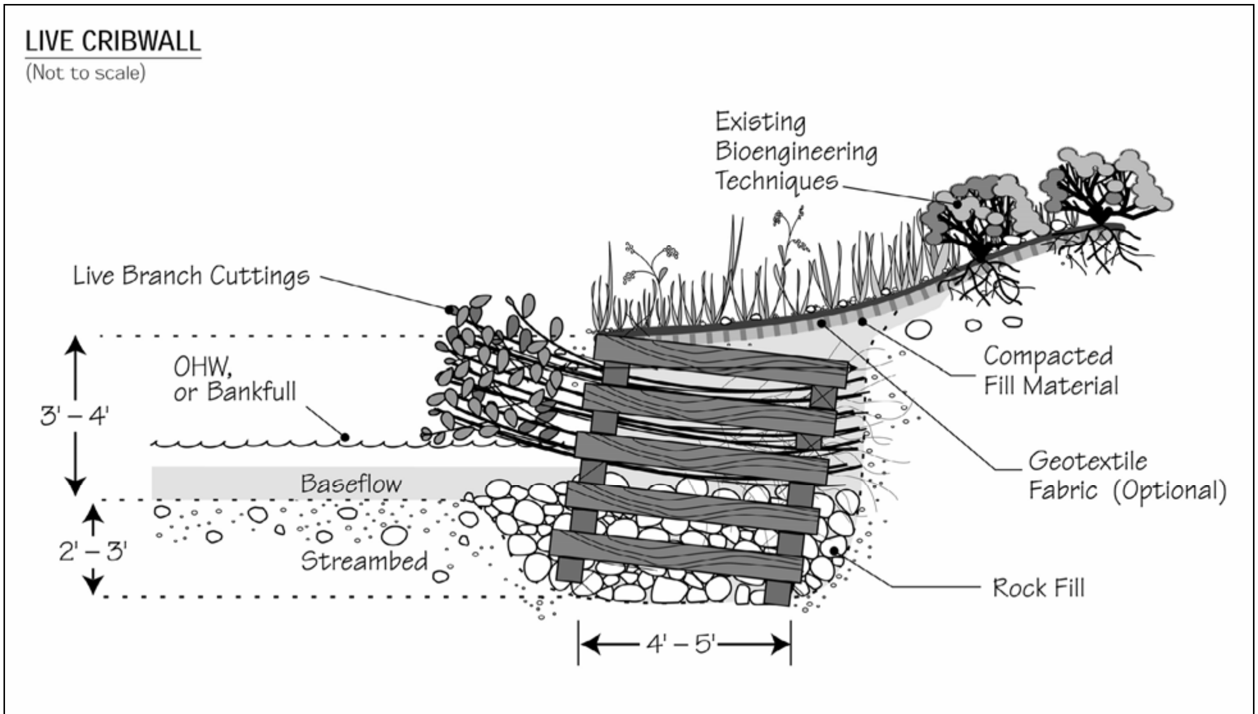


Figure 3.26 Live Cribwall (Source: USDA-FS, 2002)

Bank Shaping and Planting

Bank shaping and planting involve 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. This design 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. To determine the appropriate slope angle, slope stability analyses that take into account streambank materials, groundwater fluctuations, and bank loading conditions are recommended (FISRWG, 1998).

Case Study: Streambank Stabilization in the Thomas Fork Watershed

The Thomas Fork watershed covers 150,100 acres in Bear Lake County, Idaho and Lincoln County, Wyoming. Due to its latitude and elevation, the watershed typically experiences short, cool summers and long, cold winters. Approximately 50 percent of the watershed's annual precipitation occurs during the winter months as snow. This snow is stored in the snowpack at higher elevations and results in runoff in spring and summer. Thomas Fork is a tributary to the Bear River, upstream from where the Bear River is diverted into Bear Lake. In Idaho, the lake has been designated a Special Resource Water. Bear Lake also contains five endemic fish species.

The designated uses of Thomas Fork are cold-water biota and salmonid spawning, as well as primary and secondary recreation. The stream was first listed among Idaho's 303(d) "water quality limited stream segments" in 1996. The State's 1998 303(d) report identified sediment and nutrients as contributors to water quality impairment. The primary nonpoint sources of pollutants are cropland and rangeland, animal feeding areas, riparian areas, stream channelization, and streambank modification.

Since the mid-1990s, the Bear Lake Regional Commission has worked with partners, including the Bear Lake Soil and Water Conservation District, U.S. Department of Agriculture's Natural Resources Conservation Service, and local landowners to reduce the pollutant loading from Bear River and Thomas Fork to Bear Lake. The Soil Conservation District developed a watershed management plan, with funds provided by an Idaho state agricultural water quality project. The Bear Lake Regional Commission also received Clean Water Act Section 319 funding to work with landowners to develop and install BMPs.

Riparian and instream restoration activities began with a focus on riparian and streambank problems. Examples of BMPs installed include rock stream barbs, bank shaping and reseeding, tree revetment, rock riprap, channel armoring, fencing, animal water gaps, manure management facilities, and constructed wetlands. In addition to these measures, landowners agreed to help maintain the projects after installation.

The stabilization work resulted in a marked decrease in the amount of sediment entering Thomas Fork. Photo points, water chemistry, and surveyed stream transects were used to monitor effectiveness of the activities. The stream transects have revealed that for each foot of treated streambank, 50 cubic feet of streambank material was retained on the banks, as compared to an untreated site. Other trends show a 75% decrease in phosphorus loadings, as well as significant decreases total suspended solids and nitrogen.

Sources:

Idaho Department of Environmental Quality. 2001. *Taking Plans to Action: State of Idaho Nonpoint Source Management Program*. 2001 Report to Congress. http://www.deq.state.id.us/water/data_reports/surface_water/nps/congress_report_2001_entire.pdf. Accessed December 2005.

Poulson, M. 2003. Thomas Fork Streambank Stabilization Project. *Getting It Done: The Role of TMDL Implementation in Watershed Restoration, October 29-30, 2003, Stevenson, WA*. http://www.swwrc.wsu.edu/conference2003/pdf/Proceedings/Proceedings/Session%208B/POWERPOINT_Poulsen.pdf. Accessed March 2004.

USEPA. 1998. Idaho's Impaired Waters List Approved by EPA for 1998 (CWA Section 303(d) List). http://yosemite.epa.gov/r10/water.nsf/0/5c6b7bf2420c272888256a4800613a68/$FILE/1998303dlist.pdf. Accessed December 2005.

USEPA. 2002. *Streambank Stabilization in the Thomas Fork Watershed: Photo Monitoring Sells Landowners on Bank Stabilization*. U.S. Environmental Protection Agency, Section 319 Success Stories, Vol. III http://www.epa.gov/owow/nps/Section319III/ID.htm. Accessed June 2003.

Vegetated Gabions

Vegetated gabions (Figure 3.27) start with wire-mesh, rectangular baskets filled with small to medium rock and soil. The baskets are then laced together to form a structural toe or sidewall. Live branches (0.5 to 1 inch in diameter) are then placed on each consecutive layer between the rock filled baskets to take root, join together the structure and bind it to the slope. This method is effective for protecting steep slopes where scouring or undercutting is occurring. However, this method is not appropriate in streams with heavy bed load or where severe ice damage occurs. This method provides moderate structural support and should be placed at the base of a slope to stabilize the slope and reduce slope steepness. A stable foundation is required for the installation of these structures. When the rock size needed is not locally available, this design is effective because smaller rocks can be used. A limiting factor of this method is that it is expensive to install and to replace. These structures are relatively expensive to construct and frequently require costly repairs. This method should be combined with other soil bioengineering techniques, particularly revegetation efforts, to achieve a comprehensive streambank restoration design (FISRWG, 1998). There is often opposition to these structures based on their inability to blend in with natural settings and their general lack of aesthetically pleasing qualities (Gore, 1985).

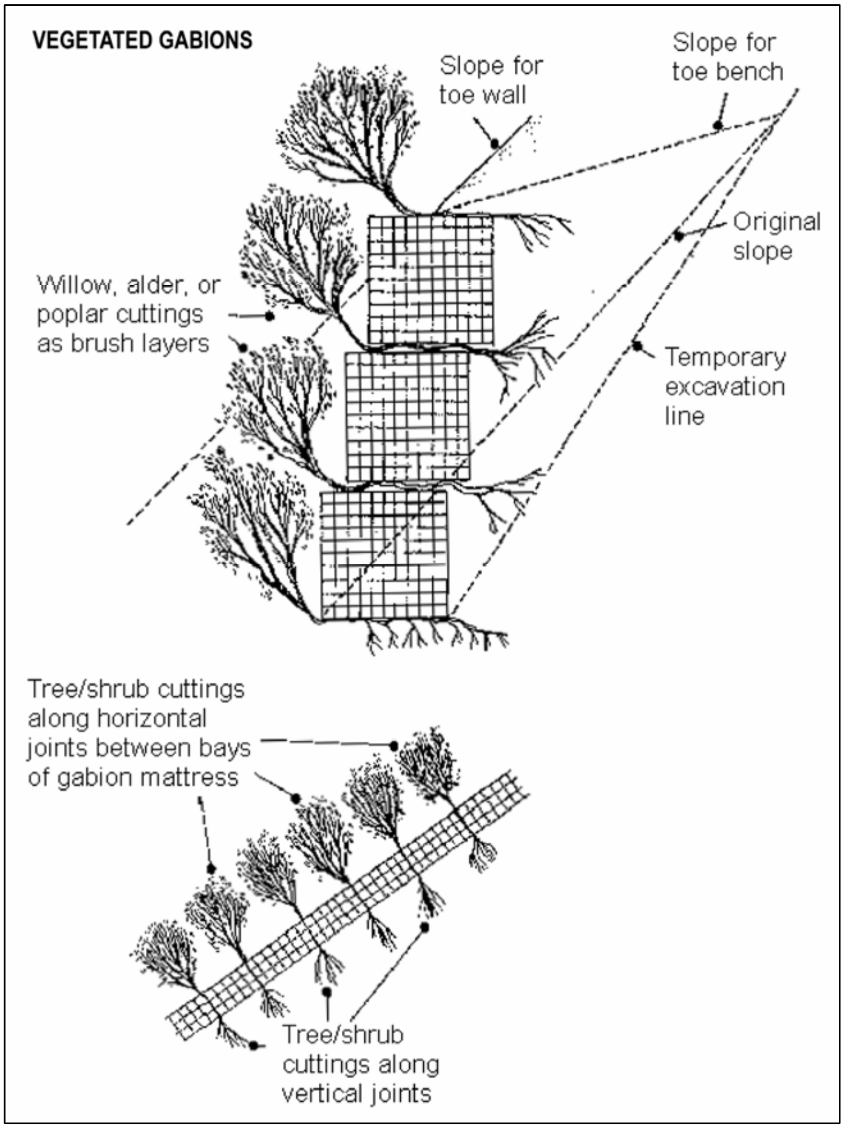


Figure 3.27 Vegetated Gabion (Source: Allen and Leech, 1997)

Installation guidelines are available from the USDA NRCS *Engineering Field Handbook, Chapter 18* (USDA-NRCS, 1992). Under EMRRP, the U.S. Army Corps of Engineers has presented research on vegetated gabions in a technical note (*Gabions for Streambank Erosion Control*), which is available at http://el.erdc.usace.army.mil/elpubs/pdf/sr22.pdf.

Rootwad Revetments

Root wads armor a bank by keeping faster moving currents away from the bank (Figures 3.28 and 3.29). They are most useful for low energy streams that meander and have out-of-bank flow conditions. Root wads should be used in combination with other soil bioengineering techniques to stabilize a bank and ensure plant establishment on the upper portions of the streambank. Stabilizing the bank will reduce streambank erosion, trap sediment, and improve habitat diversity. There are a number of ways to install root wads. The trunk can be driven into the bank, laid in a deep trench, or installed as part of a log and boulder revetment. Use tree wads that have brushy top and durable wood, such as Douglas fir, oak, hard maple, juniper, spruce, cedar, red pine, white pine, larch, or beech. Ponderosa pine and aspen are too inflexible and alder decomposes rapidly.

With the added support of a log and boulder revetment, root wads can stabilize banks of high-energy streams. Root wad span should be approximately 5 feet with numerous root protrusions. The trunk should be at least 8 to 12 feet long. Boulders should be as large as possible, but at least one and a half times the log's diameter. They should also have an irregular surface. Logs are to be used as footers or revetments and should be over 16 inches in diameter.

When logs and rootwads are well anchored, this design will tolerate high boundary shear stress. However, local scour and erosion is possible. Varying with climate and tree species used, the decomposition of the logs and rootwads will limit the life span of this design. If colonization of streambank vegetation does not take place, replacement may be required. The project site must be accessible to heavy equipment. Locating materials may be difficult in some locations and this method can be expensive (FISRWG, 1998).

Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002). Under EMRRP, the U.S. Army Corps of Engineers has presented research on rootwad composites in a technical note (*Rootwad Composites for Streambank Erosion Control and Fish Habitat Enhancement*), which is available at http://el.erdc.usace.army.mil/elpubs/pdf/sr21.pdf.

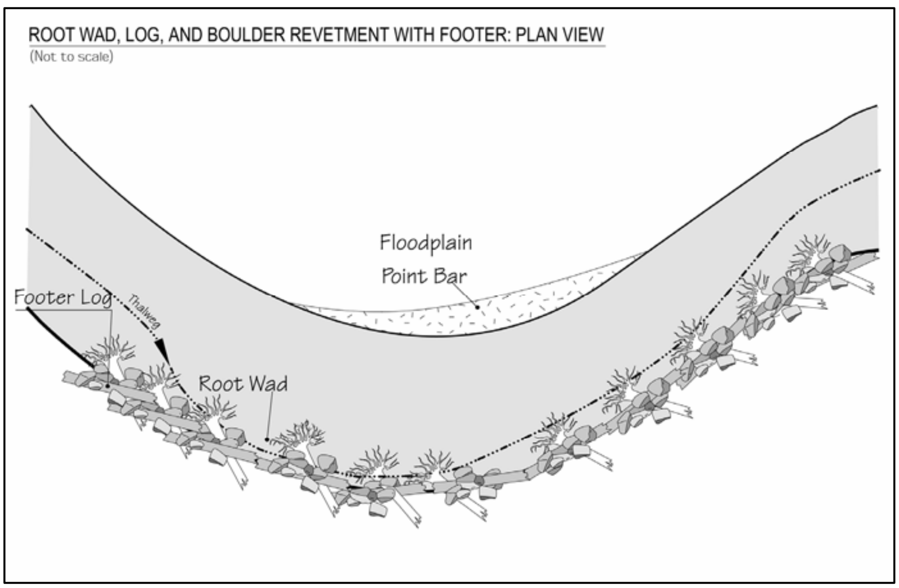


Figure 3.28 Rootwad, Log, and Boulder Revetment with Footer: Plan View (Source: USDA-FS, 2002)

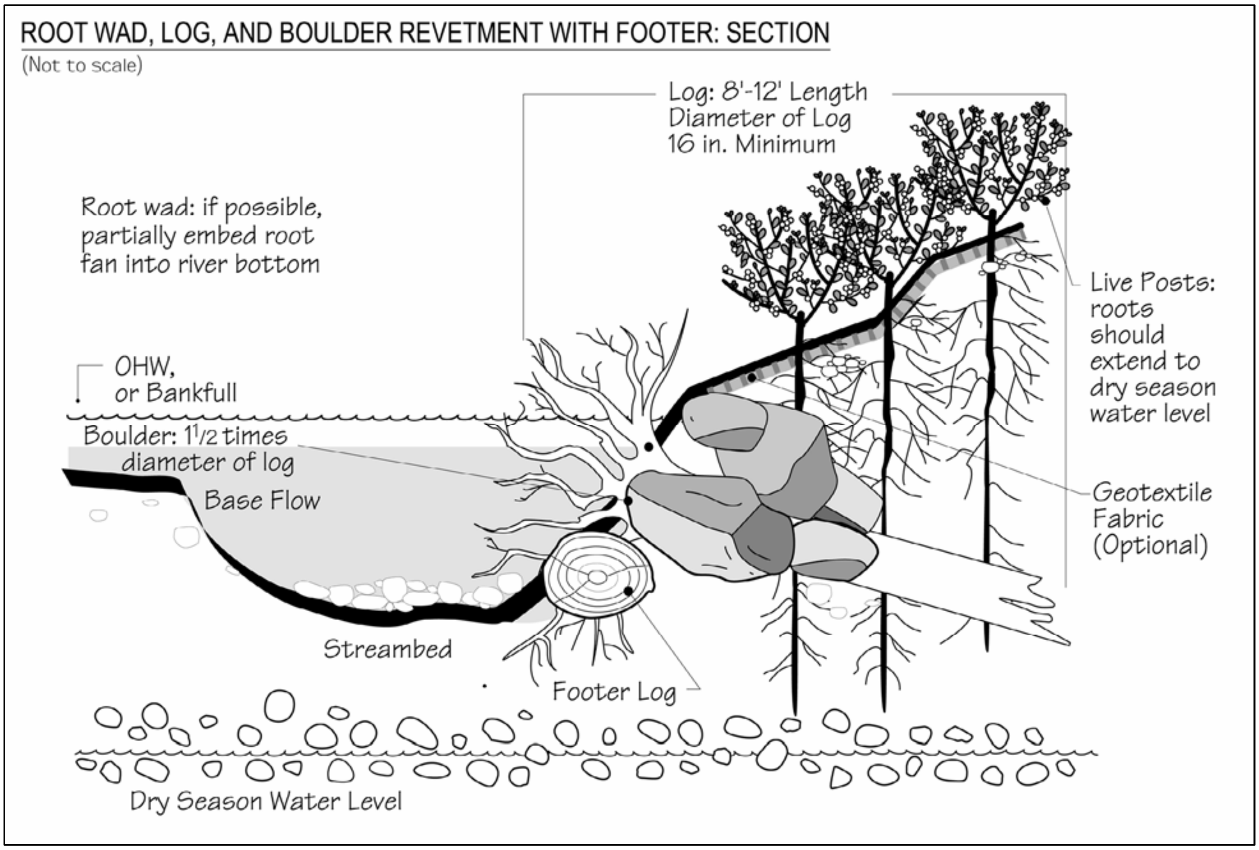


Figure 3.29 Rootwad, Log, and Boulder Revetment with Footer: Section (Source: USDA-FS, 2002)

Case Study: Coldwater Fishery Restored Through Bioengineering

Conewago Creek, just north of Arendtsville in Adams County, Pennsylvania (also known as "The Narrows") is considered one of the most scenic stream corridors in the county. The creek is listed as a "high quality coldwater fishery" and a wild trout stream by the Pennsylvania Fish and Boat Commission and is actively stocked by several local private clubs.

In the summer and early fall of 1996, Adams County received more than 90 inches of rain during severe storms, nearly 4 feet more than the county average. As a result, two sections of Conewago Creek in The Narrows were heavily damaged, resulting in severe streambank erosion. On the upper of the two sites, damage was enhanced by fallen trees, leading to erosion and channel scour. Furthermore, bedload deposits coming primarily from the upper site caused erosion on the lower section. The eroding streambanks were filling up pools, degrading the conditions necessary for fish to thrive in the creek.

In 1998, an EPA Section 319 nonpoint source grant was awarded for the restoration and stabilization of approximately 800 feet of streambank at the two sites on Conewago Creek.

The streambank at the McDannel site was severely eroded at the beginning of the project in February 1999.

Improvements to the area included measures such as smoothing and reducing the bank slope and installation of native rock and root wads along the streambank. Fallen trees at the site were used as root wads to help stabilize the toe of the bank, and the root wads and rock provided the large, heavy material necessary to stabilize the toe of the eroding slope and prevent further undercutting. The steep bank was regraded using the gravel material removed from the adjacent streambank. This process "softened" the streambank, allowing the stream to flow away from the newly stabilized banks. Following construction, local groups assisted in revegetation of the sites. The Adams County Chapter of Trout Unlimited donated trees for planting. The planted trees and grass improved the aesthetics of the site and further reduced erosion.

The project was completed on March 27, 1999. Seedlings planted continue to grow and deep pools have formed, particularly at the root wad structures. The root wads are providing excellent fish habitat and have improved trout populations at this site. Estimates from 2001 indicate that these efforts have reduced the erosion of approximately 8,000 tons of sediment from streambanks into this creek.

Sources:
USEPA. n.d. The Narrows Stream Bank Restoration and Protection Project. http://www.epa.gov/reg3wapd/nps/successstories/PApdf/narrows.pdf. Accessed March 2004.

USEPA. 2002. *Narrows Bioengineering Project: Cold-Water Fishery Restored Through Bioengineering*. U.S. Environmental Protection Agency, Section 319 Success Stories, Vol. III. http://www.epa.gov/owow/nps/Section319III/PA.htm. Accessed June 2003.

Vegetated Geogrids

Vegetated geogrids consist of layers of live branch cuttings and compacted soil with natural or synthetic geotextile materials wrapped around each soil layer (Figure 3.30). This serves to rebuild and vegetate eroded streambanks particularly on outside bends where erosion can be a problem. This system is designed to capture sediment providing a substrate for plant establishment and if properly designed and installed, these systems help to quickly establish riparian vegetation. Its benefits are similar to those of brush layering (e.g., dries excessively wet sites, reinforces soil as roots develop, which adds significant resistance to sliding or shear displacement). Due to the strength of this design and the higher initial tolerance to flow velocity, these systems can be installed on a 1:1 or steeper streambank or lakeshore. Limitations of this design include the complexity involved with constructing this system and the fairly high expense (FISRWG, 1998). When constructing this type of system, use live branch cuttings that are brushy and root readily. Also use cuttings that are 0.5 to 2 inches in diameter and 4 to 6 feet long. This type of system requires biodegradable erosion control fabric. Installation guidelines are available from the USDA-FS Soil Bioengineering Guide (USDA-FS, 2002).

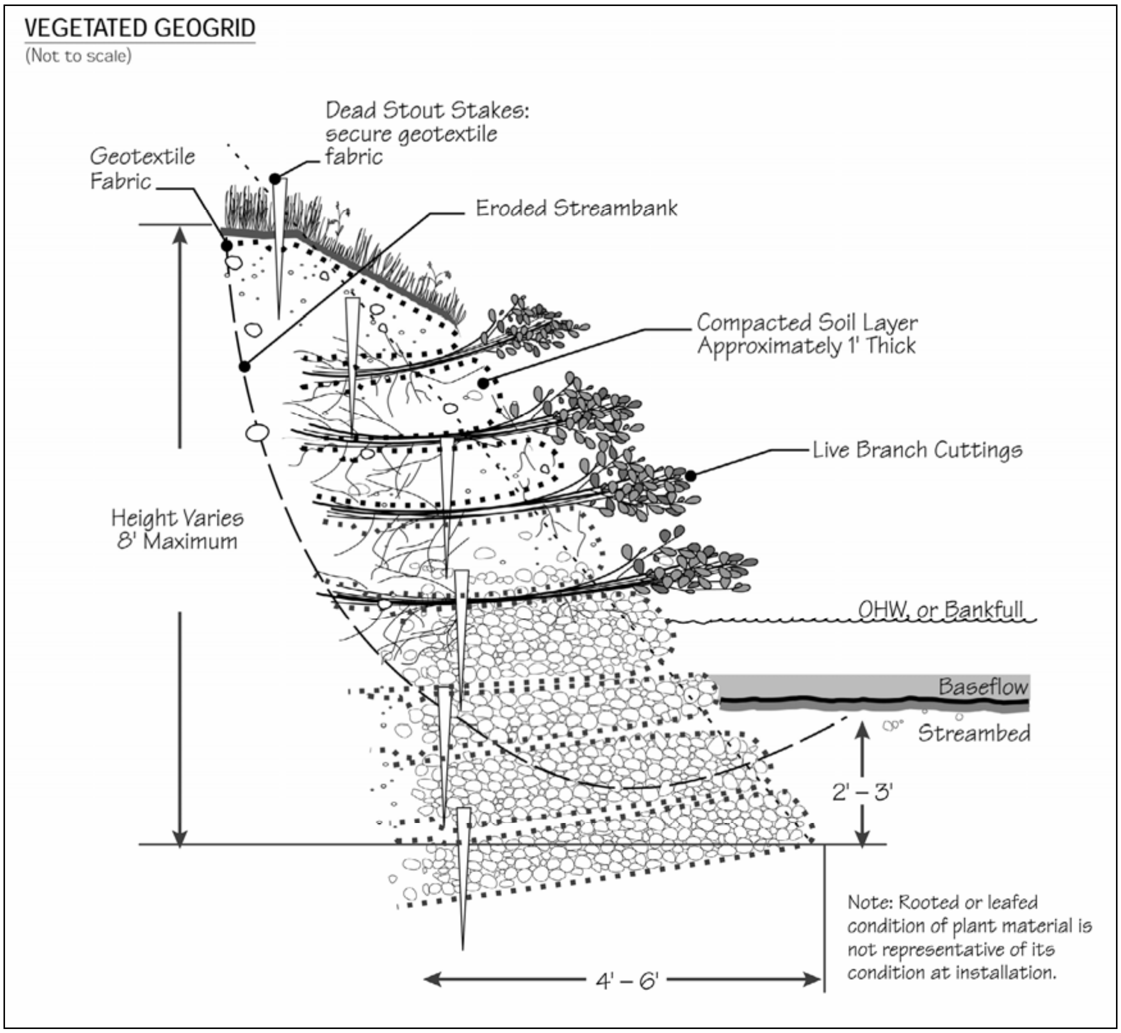


Figure 3.30 Vegetated Geogrid (Source: USDA-FS, 2002)

Vegetated Reinforced Soil Slope (VRSS)

The vegetated reinforced soil slope (VRSS) soil bioengineering system (Figures 3.31 and 3.32) 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. The VRSS system is useful for immediately repairing or preventing deeper failures, providing a structurally sound system with soil reinforcement, drainage, and erosion control (typically on steepened slope sites where space is limited). With this system, living cut branches and plants are expected to grow and perform additional soil reinforcement via the roots and surface protection via the top growth (Sotir and Fischenich, 2003).

Figure 3.31 VRSS Structure After Construction (Source: Sotir and Fischenich, 2003)

Live vegetation in the VRSS is typically installed from just above the baseflow elevation and up the face of the reconstructed streambank, acting mainly to protect the bank through immediate mechanical soil reinforcement and confinement, drainage, and, in the toe area, with rock. The VRSS system extends below the depth of scour, typically with rock, which is useful in improving infiltration and supporting the riparian zone. The internal systems such as rock, live cut branches, geogrids, geosynthetics, and geocomposites can also be configured to act as drains that redirect and/or collect internal bank seepage and transport the water to the stream via a rock toe (Sotir and Fischenich, 2003).

Plants within the VRSS structure may be selected to provide color, texture, and other attributes to add a pleasant, natural landscape appearance. Examples, of plants for the structure could include buttonbush, dogwood, willow, hybiscus, and *Viburnum* spp. Check with your local NRCS office to make sure these are appropriate for your location and for alternate suitable plant species. If a compound channel cross section is desirable near or just below the baseflow elevation, a step-back terrace may be incorporated to offer an enhanced riparian zone, where emergent aquatic plants, such as bulrush and sedges may invade over time. Although the total mass uptake may be small, they will assimilate contaminants within the water column. Aquatic wetland plants that may be installed in the VRSS adjacent to the stream include blueflag, pickerelweed, and monkey flower. Again, consult your local NRCS office for information on locally appropriate plants. VRSS systems can be constructed on slopes ranging from 1V on 2H (1:2) to 1:0.5. When constructed in step or terrace fashion, they can improve non-point pollution control by intercepting sediment and attached pollutants during overbank flows (Sotir and Fischenich, 2003).

Figure 3.32 Established VRSS Structure (Source: Sotir and Fischenich, 2003)

Additional information about VRSS systems is available from the U.S. Army Corps of Engineers technical note on VRSS (*Vegetated Reinforced Soil Slope Streambank Erosion Control*), which is available at http://el.erdc.usace.army.mil/elpubs/pdf/sr30.pdf.

Setbacks

> *Establish setbacks to minimize disturbance of land adjacent to streambanks and shorelines to reduce other impacts. Upland drainage from development should be directed away from bluffs and banks so as to avoid accelerating slope erosion.*

In addition to the soil bioengineering, marsh creation, beach nourishment, and structural practices discussed on the preceding pages of this guidance, another approach that should be considered in the planning process for shoreline and streambank erosion involves the designation of setbacks. Setbacks most often take the form of restrictions on the siting and construction of new standing structures along the shoreline. Where setbacks have been implemented to reduce the hazard of coastal land loss, they have also included requirements for the relocation of existing structures located within the designated setback area. Setbacks can also include restrictions on uses of waterfront areas that are not related to the construction of new buildings (Davis, 1987).

In most cases, states have used the local unit of government to administer the program on either a mandatory or voluntary basis. This allows local government to retain control of its land use activities and to exceed the minimum state requirements if this is deemed desirable (NRC, 1990).

Technical standards for defining and delineating setbacks also vary from state to state. One approach is to establish setback requirements for any “high hazard area” eroding at greater than 1 foot per year. Another approach is to establish setback requirements along all erodible shores because even a small amount of erosion can threaten homes constructed too close to the streambank or shoreline. Several states have general setback requirements that, while not based on erosion hazards, have the effect of limiting construction near the streambank or shoreline.

The basis for variations in setback regulations between states seems to be based on several factors, including (NRC, 1990):

- The language of the law being enacted
- The geomorphology of the coast
- The result of discretionary decisions
- The years of protection afforded by the setback
- Other variables decided at the local level of government

From the perspective of controlling NPS pollution resulting from erosion of shorelines and streambanks, the use of setbacks has the immediate benefit of discouraging concentrated flows and other impacts of storm water runoff from new development in areas close to the streambank or shoreline. In particular, the concentration of storm water runoff can aggravate the erosion of shorelines and streambanks, leading to the formation of gullies, which are not easily repaired. Therefore, drainage of storm water from developed areas and development activities located along the shoreline should be directed inland to avoid accelerating slope erosion.

The best NPS benefits are provided by setbacks that not only include restrictions on new construction along the shore but also contain additional provisions aimed at preserving and protecting coastal features such as beaches, wetlands, and riparian forests. This approach promotes the natural infiltration of surface water runoff before it passes over the edge of the bank or bluff and flows directly into the coastal waterbody. Setbacks also help protect zones of naturally occurring vegetation growing along the shore. As discussed in the section on “bioengineering practices,” the presence of undisturbed shoreline vegetation itself can help to control erosion by removing excess water from the bank and by anchoring the individual soil particles of the substrate.

Almost all states and territories with setback regulations have modified their original programs to improve effectiveness or correct unforeseen problems (NRC, 1990). Experiences have shown that procedures for updating or modifying the setback width need to be included in the regulations. For instance, application of a typical 30-year setback standard in an area whose rate of erosion is 2 feet per year results in the designation of a setback width of 60 feet. This width may not be sufficient to protect the beaches, wetlands, or riparian forests whose presence improves the ability of the streambank or shoreline to respond to severe wave and flood conditions, or to high levels of surface water runoff during extreme precipitation events. A setback standard based on the landward edge of streambank or shoreline vegetation is one alternative that has been considered (NRC, 1990; Davis, 1987).

From the standpoint of NPS pollution control, an approach that designates streambanks, shorelines, wetlands, beaches, or riparian forests as a special protective feature, allows no development on the feature, and measures the setback from the landward side of the feature is recommended (NRC, 1990). In some cases, provisions for soil bioengineering, marsh creation, beach nourishment, or engineering structures may also be appropriate since the special protective features within the designated setbacks can continue to be threatened by uncontrolled erosion of the shoreline or streambank. Finally, setback regulations should recognize that some special features of the streambank or shoreline will change position. For instance, beaches and wetlands can be expected to migrate landward if water levels continue to rise. Alternatives for managing these situations include flexible criteria for designating setbacks, vigorous maintenance of beaches and other special features within the setback area, and frequent monitoring of the rate of streambank or shoreline erosion and corresponding adjustment of the setback area.

Restoration Design Considerations

When designing a restoration project, it is important to consider the watershed as a whole as well as the specific site where restoration will occur. A watershed survey, or visual assessment, evaluates an entire watershed and can be used to help identify and verify pollutants, sources, and causes of impairments that lead to changes in streambank erosion. Additional monitoring of chemical, physical, and biological conditions may be necessary to determine if water quality is actually being affected by observed pollutants and sources. Watershed surveys can provide an accurate picture of what is occurring in the watershed. EPA’s *Volunteer Stream Monitoring: A Methods Manual* (http://www.epa.gov/owow/monitoring/volunteer/stream/vms32.html) provides a watershed survey visual assessment form that may be used. In addition to EPA’s method, a variety of visual assessment protocols have been developed by states and agencies. Designers of watershed restoration plans should look for assessment protocols that are already being used in their state or local area (USEPA, 2005c).

Photographs may also be a powerful tool that can be incorporated into watershed surveys. Photos serve as a visual reference for the site and provide before and after pictures that may be used to analyze restoration or remediation activities. In addition to taking individual photographs, aerial photographs may also provide important before and after information and can be obtained from USGS (Earth Science Information Center), USDA (Consolidated Farm Service Agencies, Aerial Photography Field Office), and other agencies (USEPA, 2005c). Refer to EPA's draft *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* for more information about watershed assessments.

Tools to analyze channels on a site-by-site basis may include geomorphic assessments such as the methodology developed by Rosgen. Geomorphic assessments help to determine river and stream characteristics such as channel dimensions, reach slope, and channel enlargement and stability. This information might help in understanding current stream conditions and may be evaluated over time to describe degradation or improvements in the stream. This may be useful for predicting future stream conditions, which can help in selecting suitable restoration or protection approaches (USEPA, 2005c).

The Rosgen geomorphic assessment approach groups streams into different geomorphic classes, based on a set of criteria that include entrenchment ratio, width/depth ratio, sinuosity, channel slope, and channel materials. Rosgen stream types can help identify streams at different levels of impairment, determine the types of hydrologic and physical factors affecting stream morphologic conditions, and choose appropriate management measures to implement if needed. More information about the Rosgen Stream Classification System is available at http://www.epa.gov/watertrain/stream_class/index.htm. Another common geomorphic assessment method is the Modified Wolman Pebble Count, which characterizes the texture (particle size) in the stream or riverbeds of flowing surface waters. It can be used alone or with Rosgen-type assessments. The composition of the streambed can provide information about the characteristics of the stream, including effects of flooding, sedimentation, and other physical impacts on a stream (USEPA, 2005c). Other assessment methods may be available from state agencies or environmental organizations.

The physical conditions of a site can provide important information about factors affecting overall stream integrity, such as agricultural activities and urban development. Runoff from cropland and feedlots can carry sediment into streams, clog existing habitat, and change geomorphological characteristics. An understanding of stream physical conditions can facilitate identification of sources and pollutants and allow for designing and implementing more effective restoration and protection strategies. Physical characterization should extend beyond the streambanks or shore and include a look at conditions in riparian areas (USEPA, 2005c).

Before choosing a practice to restore or protect eroding sreambanks, it is also important to determine what biological endpoints are desired and to consider other environmental or water quality goals. Biological endpoints may include metrics such as the number of fish surviving, number of offspring produced, impairment of reproductive capability, or morbidity. Biological endpoints can be used to evaluate the effectiveness of treatment schemes and can serve as a design parameter during restoration planning. Water quality goals, such as increasing low dissolved oxygen levels, reducing high nutrient levels, or decreasing turbidity, are also important to consider when planning restoration. For example, if turbidity is a major problem in the waterbody, planners will want to choose a method of restoration that is efficient at trapping sediment before it enters the waterbody or one that will helps sediment to settle in the stream or river. Looking at endpoints and goals before designing the method of restoration can help planners and stakeholders achieve the desired results.

When choosing from the various alternatives of engineering practices for protection of eroding streambanks and shorelines, the following factors should be taken into consideration:

- Foundation conditions
- Level of exposure to erosive forces, such as periods of high stream flow or wave action
- Availability of materials
- Initial costs and repair costs
- Past performance

Foundation conditions may have a significant influence on the selection of the type of structure to be used for shoreline or streambank stabilization. Foundation characteristics at the site must be compatible with the structure that is to be installed for erosion control. A structure such as a bulkhead, which must penetrate through the existing substrate for stability, will generally not be suitable for shorelines with a rocky bottom. Where foundation conditions are poor or where little penetration is possible, a gravity-type structure such as a stone revetment may be preferable. However, all vertical protective structures (revetments, seawalls, and bulkheads) built on sites with soft or unconsolidated bottom materials can experience scouring as incoming waves are reflected off the structures. In the absence of additional toe protection in these circumstances, the level of scouring and erosion of bottom sediments at the base of the structure may be severe enough to contribute to structural failure at some point in the lifetime of the installation.

Along streambanks, the force of the current during periods of high streamflow will influence the selection of bank stabilization techniques and details of the design. For bays, the levels of wave exposure at the site will also generally influence the selection of shoreline stabilization techniques and details of the design. In areas of severe wave action or strong currents, light structures such as timber cribbing or light riprap revetment should not be used. The effects of winter ice along the shoreline or streambank also need to be considered in the selection and design of erosion control projects.

The availability of materials is another key factor influencing the selection of suitable structures for an eroding streambank or shoreline. A particular type of bulkhead, seawall, or revetment may not be economically feasible if materials are not readily available near the construction site. Installation methods may also preclude the use of specific structures in certain situations. For instance, the installation of bulkhead pilings in coastal areas near wetlands may not always be permissible due to disruptive impacts in locating pile-driving equipment at the project site.

Costs should also be included in the decision making process for implementing practices to reduce or prevent streambank or shoreline erosion. The total cost of a shoreline or streambank protection project should be viewed as including both the initial costs (materials, labor, and planning) and the annual costs of operation and maintenance. To the extent possible, practices should be compared by their total costs. Although a particular practice may be cheaper initially, it could have operation and maintenance costs that make it more expensive in the long run. For example, in some parts of the country, the initial costs of timber bulkheads may be less than the cost of stone revetments. However, stone structures typically require less maintenance and have a longer life than timber structures. Other types of structures whose installation costs are similar may actually have a wide difference in overall cost when annual maintenance and the anticipated lifetime of the structure are considered (USACE, 1984). Environmental benefits, such as creation of habitat, should also be factored into cost evaluations.

Specific cost information for practices to protect or reduce streambank and shoreline erosion are available by contacting your local USDA Service Center, which makes available services provided by the NRCS. A list of USDA Service Centers is available at http://offices.usda.gov/scripts/ndCGI.exe/oip_public/USA_map. A list of regional and state NRCS offices is available at http://www.nrcs.usda.gov/about/organization/regions.html#state.

Information about the past performance of some of these practices (effectiveness and limitations) is available from a variety of sources, including:

- EPA's *National Menu of Best Management Practices for Storm Water Phase II* (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/menu.cfm)
- EPA's *Development Document for Proposed Effluent Guidelines and Standards for the Construction and Development Category* EPA-821-R-02-007 (2002), (http://www.epa.gov/waterscience/guide/construction/devdoc.htm)
- The Stormwater Manager's Resource Center (http://www.stormwatercenter.net)
- National Association of Home Builders (NAHB). 1995. *Storm Water Runoff & Nonpoint Source Pollution Control Guide for Builders and Developers*. National Association of Home Builders, Washington, DC. (http://www.nahbrc.org)
- National Stormwater Best Management Practices (BMPs) Database, sponsored by the American Society of Civil Engineers (ASCE) and the U.S. Environmental Protection Agency (EPA) (http://www.bmpdatabase.org)
- Oregon Association of Conservation Districts, Oregon Small Acreage Fact Sheets: *Protecting Streambanks from Erosion* (http://www.oacd.org/fs04ster.htm)
- *Urban Storm Drainage Criteria Manual: Volume 3 – Best Management Practices*. Urban Drainage And Flood Control District, Denver, Colorado, September 1999. (http://www.udfcd.org)
- The Federal Interagency Stream Restoration Working Group. 1998. *Stream Corridor Restoration Principles, Processes, and Practices.* (http://www.usda.gov/stream_restoration)
- USDA-NRCS. 1992. *Engineering Field Handbook, Chapter 18 – Soil Bioengineering for Upland Slope and Protection and Erosion Reduction* (http://www.info.usda.gov/CED/ftp/CED/EFH-Ch18.pdf)

- USDA-FS. 2002. *A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization* (http://www.fs.fed.us/publications/soil-bio-guide)
- U.S. Army Corps of Engineers.2003. *Coastal Engineering Manual, Part V*. (http://www.usace.army.mil/publications/eng-manuals/em1110-2-1100/PartV/PartV.htm)
- Fischenich and Allen. 2000. *Stream Management*. U.S. Army Corps of Engineers, Engineer Research and Development Center.

Another factor to consider when choosing an engineering practice is the position of the site where the practice will be implemented, in relation to areas upstream (shoreline) and downstream (shoreline or streambank). Practices should be evaluated in the context of the site's surrounding area to ensure that implementation of the practice does not cause erosion or other problems in surrounding areas.

Planning a Restoration Project

Several resources are available that provide detailed guidance on watershed analysis for planning and implementing watershed restoration activities (see USEPA, 2005c and USDA-FS, 2002). When planning a restoration project, it is helpful to first determine the following (USDA–FS, 2002):

- Project goal(s)
- Desired future condition of the project site, which should outline what an area should look like (based on what is capable of sustaining) and describe how the project area should be managed
- Desired aesthetics and behaviors of the people who will use the restored area
- How management of an area needs to be changed to ensure the project is a success

Characteristics of the watershed should also be considered when planning a restoration project. The infiltration capacity of watersheds can vary widely according to the structure of the watershed. For example, heavily forested watersheds with many types of vegetation typically have high infiltration rates. Vegetation intercepts and dissipates energy from raindrops. Unimpeded raindrops that reach the ground can dislodge soil and cause erosion. The presence of vegetation typically results in an abundance of organic materials that help establish highly developed root systems, which keep the soil porous and well drained. Rapid infiltration in this type of watershed results in a significant portion of precipitation becoming ground water, which is later discharged to lakes, rivers, and streams. Watersheds with little vegetation have a lower infiltration capacity, which results in poorly drained soils and less ability to intercept rainfall (USDA–FS, 2002).

Without a watershed perspective and an understanding of the physical, biological, and human processes that regulate watershed ecosystem functions, adverse side effects from restoration attempts and use of streambank and shoreline stabilization techniques may result. With a greater understanding of structure and function at a watershed scale, planners can better predict the results of restoration and stabilization activities (USDA-FS, 2002).

As discussed under the section above on restoration design considerations, it is important to incorporate classification systems such as Rosgen's methodology or the modified Wolman methodology into a restoration plan. These types of systems can be useful in classifying streams and predicting future stream conditions, which can help in selecting suitable restoration or protection approaches. It is also important to incorporate monitoring in the restoration plan to evaluate the success of the restoration effort. Refer to EPA's *Volunteer Stream Monitoring: A Methods Manual* or EPA's *Elements of a State Water Monitoring and Assessment Program* for additional information about establishing monitoring plans. Also refer to EPA's *Draft Handbook for Developing Watershed Plans to Restore and Protect Our Waters* (USEPA, 2005c) for information on developing watershed plans that will help to restore and protect water quality. The handbook provides users with a variety of useful information that may be applied during the restoration design process, including:

- Building partnerships
- Defining the scope of the project
- Gathering data
- Analyzing the data
- Estimating pollutant loads
- Setting goals to reduce pollutant loads
- Identifying potential practices to implement
- Selecting final practices
- Implementing the chosen practices
- Measuring progress

According to USDA-FS (2002), a watershed analysis should precede any stabilization work. It should address, at a minimum, functional and structural characteristics of the watershed and answer basic questions, such as:

- *What erosion processes are dominant in the watershed (e.g., surface erosion or mass wasting)? Where have they occurred or are likely to occur?*
- *What are the dominant hydrologic characteristics (e.g., total discharge, peak flows) and other notable hydrologic features and processes in the watershed (e.g., cold water seeps or groundwater recharge areas)?*
- *What is the array and landscape pattern of plant communities, and what are the seral stages in the watershed (riparian and nonriparian)? What natural processes cause these patterns (e.g., fire, wind)? How do different systems react to these natural processes based on their seral stages?*
- *What are the basic morphological characteristics of stream valleys and segments and the general sediment transport and deposition processes in the watershed (e.g., stratification using accepted classification systems)?*
- *What beneficial uses depend on aquatic resources occurring in the watershed? Which water quality parameters are critical to these uses?*
- *What is the relative abundance and distribution of species of concern that are important in the watershed (e.g., threatened or endangered species, special status species, species emphasized in other plans)? What is the distribution and character of their habitats?*
- *What current and past human uses (e.g., Forest Service management practices and private and public use patterns), on and adjacent to forest land, may be affecting the watershed?*

USDA-FS (2002) provides a more detailed discussion of watershed analyses.

- Resources containing more detailed information
- Worksheets that help users work through the planning process

Reviewing and understanding the historic ecology of the site and of the undisturbed areas in similar ecological settings often serve as benchmarks for determining the desired future condition. Aerial photographs can be a valuable tool for comparing differences over time, including land- and social-use patterns (USDA–FS, 2002).

For a soil bioengineering project to be successful, it is critical that planners recognize the static and dynamic relationships in natural systems (e.g., the relationship between stream and riparian ecosystems). Failure to notice these types of relationships can interrupt the ecological integrity and prevent a successful restoration project from occurring. Planners should also understand the connection between areas and the people who will use them. Reviewing the historical photographs and written records, topographical maps, soil type, fishing productivity records, and stream and watershed analysis can assist planners with identifying the correct relationships (USDA–FS, 2002).

Planners should use long-term solutions for soil bioengineering projects that fix the problem, rather than quick-fix technologies that only treat symptoms. Determine the nature of the problem by using a holistic analytical approach, assessing upstream and downstream conditions, lateral and vertical conditions, and their connections to the problem area. This type of assessment will help determine whether the problem is unique or if it is symptomatic of other problems in the watershed. Planners should be certain to gain a through understanding of the underlying problem and how it interacts with other natural processes in the watershed (USDA-FS, 2002).

For stabilization projects to be successful, it must be a collaborative effort. Any person or group with a stake in clean water is a potential partner. Planners should look for partners in local and national land and wildlife conservation organizations and clubs, civic groups, faith-based groups, schools and colleges, and businesses. Other agencies, such as NRCS, the U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency, state fish and games departments, state departments of natural resources, and local water districts are potential partners that could contribute funding and expertise to a project (USDA-FS, 2002).

Monitoring and Maintenance of Structures

Monitoring is critical for a project to be successful. By monitoring a site, you may determine if any structures are in need of maintenance. When performing monitoring, note which plants are doing well and which did not survive. Does the site appear to be recovering? Also note conditions, such as soil moisture, aspect, sun-to-shade ratio, and degree of slope. Has the area been trampled, grazed, or driven over? Have any of the structures (e.g., tree revetments) shifted? Other aspects that you could monitor are (USDA-FS, 2002):

- Keeping track of where plants were harvested—is there a correlation between growth rate of certain cuttings and the "mother" plants?
- Is the installation functioning as designed?
- Which areas are maturing more rapidly than others?
- Are seeds sprouting in the newly formed beds?

- Which plants have invaded the site through natural succession?
- What has sprouted in the second season?
- Which areas are experiencing difficulty and why?
- Is the bank stabilizing or washing away and why?
- Is something occurring that is unexpected?
- Which techniques are succeeding?
- Are any of the structures failing?

USDA NRCS' *The Practical Streambank Bioengineering Guide* (Bentrup and Hoag, 1998) provides an example monitoring form and is available at http://www.engr.colostate.edu/~bbledsoe/CE413/idpmcpustguid.pdf. The monitoring sheet is also available in Appendix C of USDA-FS, 2002, at http://www.fs.fed.us/publications/soil-bio-guide/guide/appendices.pdf.

During the first few years after installation, maintenance is necessary until vegetation becomes established and the bank stabilizes. Structures may shift or you may notice something that was left undone. Once vegetation is established, projects should become self-sustaining and require little or no maintenance. Be sure the site is managed to give the treatment every chance to be effective over a long period of time (USDA-FS, 2002).

Common maintenance tasks include (USDA-FS, 2002; Bentrup and Hoag, 1998):

- Remove debris and weeds that may shade and compete with cuttings
- Secure stakes, wire, twine, etc.
- Control weeds
- Repair weakened or damaged structures (including fences)
- Replant and reseed as necessary (it is not uncommon for a flood to occur days after installation)

Planting success varies from project to project. Bentrup and Hoag, 1998 provide the following potential growth success rates:

Pole Plantings	*70-100%*
Live Fascines	*20-50%*
Brush Layering	*10-70%*
Post Plantings	*50-70%*

It is beneficial to inspect the project every other week for the first 2 months after installation, once a month for the next 6 months, and then every other month for 2 years, at least. You should also inspect the project after heavy precipitation, flooding, snowmelt, drought, or any extraordinary occurrence. Assess damage from flooding, wildlife, grazing, boat wakes, trampling, drought, and high precipitation (USDA-FS, 2002). Additional information about monitoring is available from USDA NRCS' *The Practical Streambank Bioengineering Guide* (Bentrup and Hoag, 1998).

Plan and design all streambank, shoreline, and navigation structures so that they do not transfer erosion energy or otherwise cause visible loss of surrounding streambanks or shorelines.

Maintenance varies with the structural type. For stone revetments, the replacement of stones that have been dislodged is necessary; timber bulkheads need to be backfilled if there has been a loss of upland material, and broken sheet pile should be replaced as necessary. Gabion baskets should be inspected for corrosion failure of the wire, usually caused either by improper handling during construction or by abrasion from the stones inside the baskets. Baskets should be replaced as necessary since waves will rapidly empty failed baskets.

Steel, timber, and aluminum bulkheads should be inspected for sheet pile failure due to active earth pressure or debris impact and for loss of backfill. For all structural types not contiguous to other structures, lengthening of flanking walls may be necessary every few years. Through periodic monitoring and required maintenance, a substantially greater percentage of coastal structures will perform effectively over their design life. Since streambank or shoreline protection projects can transfer energy from one area to another, which causes increased erosion in the adjacent area, the possible effects of erosion control measures on adjacent properties should be routinely monitored.

References[1]

Academy of Natural Sciences. 2002. *Manatawny Creek: Ecological Studies of Dam Removal*. http://www.acnatsci.org/research/pcer/manatawnyresearch.html. Accessed July 2002.

Adams, S., and O.E. Maughan. 1986. The effects of channelization on the benthic assemblage in a southeastern Oklahoma stream. *Proceedings of the Oklahoma Academy of Science* 66:35-36.

Aicardo, R. 1996. Screening of polymers to determine their potential use in erosion control on construction sites. In *Proceedings from Conference held at College of Southern Idaho: Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide, May 6–8, 1996, Twin Falls, Idaho*. University of Idaho Miscellaneous Publication No. 101-96.

Allan, J.D. 1995. *Stream Ecology: Structure and Function of Running Waters.* Kluwer Academic Publishers, Dordrecht, The Netherlands. 400 p.

Albright Seed Company. 2002. *Albright Seed Company*. http://www.albrightseed.com/leaflittermar2002.htm. Accessed April 2004.

Allen, H.H., and C.V. Klimas. 1986. *Reservoir Shoreline and Revegetation Guidelines*. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Allen, H.H. and J.R. Leech. 1997. *Bioengineering for Streambank Erosion Control: Report 1 Guidelines*. U.S. Army Corps of Engineers, Environmental Impact Research Program, Technical Report EL-97-8. http://el.erdc.usace.army.mil/elpubs/pdf/trel97-8.pdf. Accessed October 2004.

American Rivers. No date a. *Dam Removal: Frequently Asked Questions*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1725.

American Rivers. No date b. *Data Collection: Researching Dams and Rivers Prior to Removal*. http://www.amrivers.org/doc_repository/Reseaching%20a%20Dam%20-%20-%20Data%20Collection.pdf. Accessed October 2004.

American Rivers. 1999. *Dam Safety: Protecting Communities and Ecosystems from Dam Failure*.

American Rivers. 2002a. *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1796. Accessed October 2004.

American Rivers. 2002b. *Obtaining Permits to Remove a Dam*.

American Rivers. 2003. 2003 Salmon Migration Report Card: Federal Dam Managers on Columbia-Snake Get Failing Grades – River Conditions Violate Clean Water Act, Endangered

[1] This reference list does not include references used for case studies. All case study references are included with each individual case study.

Species Act. http://wildsalmon.org/library_files/AR_PR_salmon_rep_card_2003. Accessed September 2005.

American Rivers and Trout Unlimited. 2002. *Exploring Dam Removal: A Decision Making Guide*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1802. Accessed October 2004.

American Society of Civil Engineers (ASCE). 1986. *Lessons Learned from Design, Construction, and Performance of Hydraulic Structures*. American Society of Civil Engineers, Hydraulics Division, Hydraulic Structures Committee, New York, NY.

Anderson, S. 1992. Studies begin on Kaneohe Bay's toxin problem. *Makai* 14(2):1,3. University of Hawaii Sea Grant College Program.

Anderson, J. 1995. *Analysis of Snake River Spill*. University of Washington. http://www.cbr.washington.edu/papers/jim/testimonies/senate.june.html. Accessed September 2005.

Andrews, J. 1988. *Anadromous Fish Habitat Enhancement for the Middle Fork and Upper Salmon River*. Technical Report DOE/BP/17579-2. U.S. Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife, Portland, OR.

Anthony, P. 1998. *The Snake River Levee System Report*. Jackson Hole Conservation Alliance. http://www.jhalliance.com/reports/levee.pdf . Accessed April 2004.

Ashley, P.R. and M. Berger. 1997. *Columbia River Wildlife Mitigation Habitat Evaluation Procedures Report*. Prepared for the U.S. Department of Energy. Portland, OR. http://www.efw.bpa.gov/Publications/W39607-1.pdf. Accessed August 2005.

Aspen Institute. 2002. *Dam Removal: A New Option for a New Century*. The Aspen Institute, Queenstown, MD. http://www.aspeninstitute.org/AspenInstitute/files/CCLIBRARYFILES/FILENAME/0000000074/damremovaloption.pdf. Accessed May 2004.

Associated Press and the Herald Staff. 2002. Corps modifying dams. *Tri-City Herald.* http://www.snakedams.com/news/022102.html. Accessed July 2002.

Atlantic States Marine Fisheries Commission. 2002. *Beach Nourishment: A Review of the Biological and Physical Impacts*. ASMFC Habitat Management Series # 7. http://www.asmfc.org/publications/habitat/beachNourishment.pdf. Accessed August 2005.

Barbiero, R.P., S.L. Ashby, and R.H. Kennedy. 1996. The effects of artificial circulation on a small northeastern impoundment. *Water Resources Bulletin*. 32(3):575-584.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and*

Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Barbour, M.T., and J.B. Stribling. 1991. Use of habitat assessment in evaluating the biological integrity of stream communities. In *Biological Criteria: Research and Regulation*, ed. EPA-440/5-91-005. U.S. Environmental Protection Agency, Office of Water, pp. 25-38. Washington, DC.

Benke. 2001. Importance of flood regime to invertebrate habitat in an unregulated river-floodplain ecosystem. *Journal of the North American Benthological Society* 20(2): 225-240.

Bentrup, G. and J.C. Hoag, 1998. *The Practical Streambank Bioengineering Guide*. USDA NRCS Plant Material Center, Aberdeen, Idaho. http://www.engr.colostate.edu/~bbledsoe/CE413/idpmcpustguid.pdf. Accessed December 2004.

Biedenharn, D.S., C.M. Elliott, and C.C. Watson. 1997. *The WES Stream Investigation and Streambank Stabilization Handbook*. Prepared for U.S. Environmental Protection Agency by U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Biedenharn, D.S. and L.C. Hubbard. 2001. *Design Considerations for Siting Grade Control Structures*. U.S. Army Corps of Engineers, ERDC/CHL CHETN-VII-3. http://chl.erdc.usace.army.mil/library/publications/chetn/pdf/chetn-vii-3.pdf. Accessed November 2004.

Bis, B., A. Zdanowicz and M. Zalewski. 2000. Effects of catchment properties on hydrochemistry, habitat complexity, and invertebrate community structure in a lowland river. *Hydrobiologia* 42: 369-387.

BioFence. No date. *BioFence*. http://biofence.com:85/coinfo.htm. Accessed April 2004.

Blaha, K. 2000. Source water protection through land acquisition. *Nonpoint Source News-Notes*. http://notes.tetratech-ffx.com/newsnotes.nsf. Issue 62. Accessed June 2003.

Bowie, A.J. 1981. Investigation of vegetation for stabilizing eroding streambanks. Appendix C to *Stream Channel Stability*. U.S. Department of Agriculture Sedimentation Laboratory, Oxford, MS. Original not available for examination. Cited in Henderson, 1986.

Brate, Arthur. 2004. Dam rehabilitation a comprehensive approach to rehabbing small watershed dams. *Resource* 11(2).

Brookes, A. 1998. *Channelized Rivers; Perspectives for Environmental Managers*. John Wiley & Sons, Chichester, England.

Brown, W., and D. Caraco. 1997. Muddy water in—Muddy water out? A critique of erosion and sediment control plans. *Watershed Protection Techniques* 2(3):393–403.

Burch, C.W., P. R. Abell, M. A. Stevens, R. Dolan, B. Dawson, and F.D. Shields, Jr. 1984. *Environmental Guidelines for Dike Fields*. Technical Report E-84-4. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Bureau of Labor Statistics (BLS). 2001. *Consumer Price Indexes*. http://www.bls.gov/cpi. Accessed June 2003.

Burress, R.M., D.A. Krieger, and C.H. Pennington. 1982. *Aquatic Biota of Bank Stabilization Structures on the Missouri River, North Dakota*. Technical Report E-82-6. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Cada, G.F. 2001. The development of advanced hydroelectric turbines to improve fish passage survival. Abstract. *Fisheries*. 26(9):14-23. http://hydropower.inel.gov/turbines/pdfs/amfishsoc-fall2001.pdf. Accessed September 2005.

California Department of Boating and Waterways and State Coastal Conservancy. 2002. *California Beach Restoration Study*. Sacramento, California. http://dbw.ca.gov/beachreport.asp. Accessed August 2005.

CSWRCB. 2005. *California Nonpoint Source Encyclopedia*. California State Water Resources Control Board. Sacramento, CA. http://www.swrcb.ca.gov/nps/encyclopedia.html. Accessed August 2005.

CASQA. 2003. *Drainage System Maintenance*. California Stormwater Quality Association. California Stormwater BMP Handbook, SC-74. http://www.cabmphandbooks.com/Documents/Municipal/SC-74.pdf. Accessed November 2004.

CWP. 1997a. Keeping soil in its place. *Watershed Protection Techniques* 2(3): 418–423, Center for Watershed Protection.

CWP. 1997b. Improving the trapping efficiency of sediment basins. *Watershed Protection Techniques* 2(3): 434–439, Center for Watershed Protection.

CWP. 1997c. The limits of settling. *Watershed Protection Techniques* 2(3):429–433, Center for Watershed Protection.

CWP. 1997d. Strengthening silt fence. *Watershed Protection Techniques* 2(3):424–428, Center for Watershed Protection.

Chesapeake Bay Program. 1997. *Protecting Wetlands: Tools for Local Governments in the Chesapeake Bay Region*. Chesapeake Bay Program, Annapolis, MD.

Cohen, R. 1997. *Fact Sheet #9: The Importance of Protecting Riparian Areas Along Smaller Brooks and Streams*. Rivers Advocate, Riverways Program, Massachusetts Department of Fisheries, Wildlife and Environmental Law Enforcement. http://www.state.ma.us/dfwele/river/rivfact9.htm. Accessed May 2003.

Colonnello, G. 2001. Physico-chemical comparison of the Manamo and Macereo rivers in the Orinoco delta after the 1965 Manamo dam construction. *Intercencia* 26(4): 136-143.

Colt, J. 1984. *Computations of Dissolved Gas Concentrations in Water as Functions of Temperature, Salinity and Pressure*. Special Publication No. 14. American Fisheries Society, Bethesda, MD.

Conwed Fibers. No date. Conwed Fibers. http://www.conwedfibers.com. Accessed May 2003.

Copeland, R.R., D.N. McComas, C.R. Thorne, P.J. Soar, M.M. Jones, and J.B. Fripp. 2001. *Hydraulic Design of Stream Restoration Projects*. ERDC/CHL TR-01-28. U.S. Army Corps of Engineers, Washington, DC.

Cwikiel, W. 1996. *Living with Michigan Wetlands: A Landowner's Guide*. Tip of the Mitt Watershed Council, Conway, MI.

Dadswell, M.J. 1996. The removal of Edwards Dam, Kennebec River, Maine: Its effects on the restoration of anadromous fishes. Draft environmental impact statement, Kennebec River, Maine, Appendices 1-3. In *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. American Rivers, Washington, D.C.

Davis, C.A. 1987. A strategy to save the Chesapeake Shoreline. *Journal of Soil and Water Conservation* 42(2):72-75.

Dawson, Spofford, Pfeiffer. May 1996. The physical effects of polyacrylamide on natural resources. In *Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide*. Miscellaneous Publication 101-96, University of Idaho.

Décamps, H., M. Fortune, F. Gazelle, and G. Pautou. 1988. Historical influence of man on the riparian dynamics of a fluvial landscape. *Landscape Ecology*. 1(3): 63-173.

Deering, J.W. 2000a. *Allowance Item for Soil Erosion and Sediment Control Plan/Measures*. John W. Deering, Inc., Bethel, CT.

Deering, J.W. 2000b. *Phasing, Sequence, and Methods*. John W. Deering, Inc., Bethel, CT.

Dehart, M. 2003. *Summary of Documented Benefits of Spill*. Fish Passage Center. http://www.fpc.org/documents/memos/227-03.pdf. Accessed September 2005.

Delaware DNREC. 2003. *Delaware Erosion and Sediment Control Handbook*. Delaware Department of Natural Resources and Environmental Control, Dover, Delaware. http://www.dnrec.state.de.us/DNREC2000/Divisions/Soil/Stormwater/New/Delaware%20ESC%20Handbook_06-05.pdf. Accessed August 2005.

Delaware Riverkeeper. No date. *Dam Removal and River Restoration*. http://www.delawareriverkeeper.org/factsheets/dam_removal.html. Accessed May 2003.

Deliman, P.N., R.H. Glick, and C.E. Ruiz. 1999. *Review of Watershed Water Quality Models*. Technical Report W-99-1, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Dillaha, T.A., J.H. Sherrard, and D. Lee. 1989. Long-term effectiveness of vegetative filter strips. *Water Environment and Technology* (November 1989):419-421.

Dodge, N.A. 1989. Managing the Columbia River to meet anadromous fish requirements. In *Proceedings Waterpower '89*, American Society of Civil Engineers, Niagara Falls, NY August 23-25, 1989.

Dorthch, M.S. 1997. *Water Quality Considerations in Reservoir Management*. Water Resources Update, Universities Council on Water Resources, Southern Illinois, University Carbondale, IL.

Doyle, M.W., E.H. Stanley, M.A. Luebke, and J.M. Harbor. 2000. *Dam Removal: Physical, Biological, and Societal Considerations.* American Society of Civil Engineers Joint Conference on Water Resources Engineering and Water Resources Planning and Management. Minneapolis, MN.

Dryden Aqua. 2002. *Degassing*. http://www.drydenaqua.com/degassing/degas.htm. Accessed July 2002.

Duke Engineering & Services, Inc. 2000. *Fish Entrainment: Lake Chelan Hydroelectric Project*. FERC Project No. 637. http://www.chelanpud.org/relicense/study/reports/4010_1.pdf. Accessed April 2004.

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman, New York, 818p.

EMC2. 2001. *Milltown Reservoir Sediments Site Draft Combined Feasibility Study*. http://www.epa.gov/region08/superfund/sites/fs_narrative.pdf. Accessed October 2004.

Entry, J.A., and R.E. Sojka. 1999. Polyacrylamide application to soil reduces the movement of microorganisms in water. In *1999 Proceedings of the International Irrigation Show*. Irrigation Association, Orlando, FL, November 9, 1999, pp. 93–99.

Environmental Defense. 2002. *Impacts of Corps Projects*. http://www.edf.org/documents/2072_ImpactsCorpsProjects.pdf. Accessed April 2004.

Environmental Law Institute. 1998. *Almanac of Enforceable State Laws to Control Nonpoint Source Water Pollution*. Environmental Law Institute, Washington, DC. http://www.eli.org. Accessed June 2003.

EPRI. 1990. *Assessments and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges*. Electric Power Research Institute, EPRI GS-7001. Aquatic Systems Engineering, Wellsboro, Pennsylvania.

EPRI. 1999. *Fish Protection at Cooling Water Intakes: Status Report*. Electric Power Research Institute. TR-114013.

Erosion Control Systems, Inc., personal communication, March 14, 2001.

EUCC. 1999. *European Code of Conduct for the Coastal Zone*. European Union for Coastal Conservation. http://www.coastalguide.org/code. Accessed August 2005.

FAO. 1997. *Management of Agricultural Drainage Water Quality*. Food and Agriculture Organization of the United Nations, International Commission on Irrigation and Drainage. Water Reports 13. http://www.fao.org/docrep/w7224e/w7224e00.htm#Contents.

FAO. 2001. *Dams, Fish and Fisheries: Opportunities, Challenges and Conflict Resolutions*. Food and Agriculture Organization of the United Nations Fishery Department. Rome, Italy. http://www.fao.org/documents. Accessed August 2005.

Feather River Hatchery. No date. *Feather River Hatchery: Fish Ladder*. http://www.dfg.ca.gov/lands/fh/feather/ladder.htm. Accessed May 2003.

FHWA. 2001. *River Engineering for Highway Encroachments: Highways in the River Environment.* Hydraulic Design Series Number 6, Publication Number FHWA NHI 01-004, U.S. Department of Transportation, Federal Highway Administration, Washington, DC. http://isddc.dot.gov/OLPFiles/FHWA/010589.pdf. Accessed August 2005.

FISRWG. 1998. *Stream Corridor Restoration: Principles, Processes, and Practices*. Federal Interagency Stream Restoration Working Group, U.S. Department of Commerce, National Technical Information Service. http://www.nrcs.usda.gov/technical/stream_restoration. Accessed June 2003.

Fischenich, C. 2000. *Impacts of Stream Stabilization Structures: WRAP Report*. ERDC Environmental Laboratory. http://www.nwo.usace.army.mil/html/od-rmt/stabimpactsjcf_wrap.pdf. Accessed September 2005.

Fischenich, C. 2001. Stability Thresholds for Stream Restoration Materials. EMRRP Technical Notes Collection (ERDC TN EMRRP-SR-29) U.S. Army Corps of Engineer Research and Development Center, Vicksburg, MS.

Fischenich, C. 2003. *Effects of Riprap on Riverine and Riparian Ecosystems*. U.S. Army Corps of Engineers. Engineer Research and Development Center. http://el.erdc.usace.army.mil/wrap/pdf/trel03-4.pdf. Accessed September 2005.

Fischenich, C. and H. Allen. 2000. *Stream Management*. U.S. Army Corps of Engineers, Engineer Research and Development Center. ERDC/EL SR-W-00-1.

Findley, D.I., and K. Day. 1987. Dissolved oxygen studies below Walter F. George Dam. In *Proceedings: CE Workshop on Reservoir Releases*, Misc. Paper E-87-3. U.S. Army Corp of Engineers Waterways Experiment Station, Vicksburg, MS.

Fontane, D.G., W.J. Labadie, and B. Loftis. 1981. *Optimal Control of Reservoir Discharge Quality Through Selective Withdrawal: Hydraulic Laboratory Investigation*. Prepared by Colorado State University and the Hydraulics Laboratory, Waterways Experimental Station, for the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Franklin, S.B., J.A. Kupfer, S.R. Pezeshki, R.A. Hanson, T.L. Scheff and R.W. Gentry. 2001. A comparison of hydrology and vegetation between a channelized stream and a nonchannelized stream in western Tennessee. *Physical Geography* 22(3): 254-274.

Freeman, P.H. 1977. Large Dams and the Environment, Recommendations for Development Planning. In *International Institute for Environment and Development*.

Friends of the Earth (FOE), American Rivers, and Trout Unlimited. 1999. *Dam Removal Success Stories: Restoring Rivers through Selective Removal of Dams that Don't Make Sense*. http://www.amrivers.org/doc_repository/SuccessStoriesReport.pdf. Accessed October 2004.

FOR. 1999. *Rivers Reborn: Removing Dams and Restoring Rivers in California*. Friends of the River, Sacramento, California. http://www.friendsoftheriver.org/Publications/RiversReborn/main3.html. Accessed June 2003.

Fulford, E.T. 1985. Reef type breakwaters for shoreline stabilization. In *Coastal Zone '85*, American Society of Civil Engineers, New York, NY, pp. 1776-1795.

Gallagher, J.W., and G.V. Mauldin. 1987. Oxygenation of releases from Richard B. Russell Dam. In *Proceedings: CE Workshop on Reservoir Releases*, U.S. Army Corp of Engineers Waterways Experiment Station, Vicksburg, MS. Misc. Paper E-87-3.

Galli, J. 1991. *Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices*. Metropolitan Washington Council of Governments. Maryland Department of the Environment. Washington, DC. 188 pp.

Goldman, S.J., K. Jackson, and T.A. Borstztynksy. 1986. *Erosion and Sediment Control Handbook*. McGraw-Hill, Inc., New York, NY.

Gore, J.A., ed. 1985. *The Restoration of Rivers and Streams*. Butterworth, Boston, MA.

Gray, D.H., and A.T. Leiser. 1989. *Biotechnical Slope Protection and Erosion Control*. Krieger Publishing Co, Florida.

Gray, D.H. and R.B. Sotir. 1996. *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*. John Wiley and Sons, New York, NY.

Hall, V.L., and J.D. Ludwig. 1975. *Evaluation of Potential Use of Vegetation for Erosion Abatement Along the Great Lakes Shoreline*. MP-7-75. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, VA.

Hamilton, P. 1990. Modelling salinity and circulation for the Columbia River estuary. *Progress in Oceanography* 25:113-156.

Hansen, R.P., and M.D. Crumrine. 1991. *The Effects of Multipurpose Reservoirs on the Water Temperature of the North and South of Santiam Rivers, Oregon*. Water Resources Investigations, Report 91-4007. U.S. Geological Survey, prepared in cooperation with the U.S. Army Corps of Engineers, Portland, OR.

Hardaway, C.S., G.R. Thomas, and J.-H. Li. 1991. *Chesapeake Bay Shoreline Study: Headland Breakwaters and Pocket Beaches for Shoreline Erosion Control, Final Report*. Virginia Institute of Marine Science, Gloucester Point, VA.

Hardaway, C.S., and J.R. Gunn. 1989. Elm's Beach Breakwater Project - St. Mary's County, Maryland. In *Proceedings Beach Technology '89*, Tampa, FL.

Hardaway, C.S., and J.R. Gunn. 1991. Working Breakwaters. *Civil Engineering* October 1991:64-66.

Harris, G.G., and W.A. Van Bergeijk. 1962. Evidence that the lateral-line organ responds to near-field displacements of sound sources in water. *Journal of the Acoustic Society of America* 34:1831-1841.

Harshbarger, E.D. 1987. Recent developments in turbine aeration. In *Proceedings: CE Workshop on Reservoir Releases*. Misc. Paper E-87-3. U.S. Army Corp of Engineers Waterways Experiment Station, Vicksburg, MS.

Hauser, Gary, Tennessee Valley Authority. 1992. Personal communication.

Hauser, G.E., M.D. Bender, and M.K. McKinnon. 1989. *Model Investigation of Douglas Tailwater Improvements*. Technical Report No. WR28-1-590-143. Tennessee Valley Authority, Norris, TN.

Hauser, G.E., M.C. Shiao, and M.D. Bender. 1990a. *Modeled Effects of Extended Pool Level Operations on Water Quality*. Technical Report No. WR28-2-590-148. Tennessee Valley Authority Engineering Laboratory, Norris, TN.

Hauser, G.E., M.C. Shiao, and R.J. Ruane. 1990b. *Unsteady One-Dimensional Modelling of Dissolved Oxygen in Nickajack Reservoir*. Technical Report No. WR28-1-590-150. Tennessee Valley Authority Engineering Laboratory, Norris, TN.

Hehnke, M., and C.P. Stone. 1978. Value of riparian vegetation to avian populations along the Sacramento River system. In *Strategies for Protection and Management of Floodplains, Wetlands, and other Riparian Ecosystems,* ed. R.R. Johnson and J.F. McCormick. U.S. Forest Service, Washington DC. GTR-WO-12. Original not available for examination. Cited in Henderson and Shields, 1984.

Henderson, J.E. 1986. Environmental design for streambank protection projects. *Water Resources Bulletin* 22(4):549-558.

Henderson, J.E., and F.D. Shields Jr., 1984. *Environmental Features for Streambank Protection Projects*. Technical Report E-84-11.U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Higgins, J.M., and B.R. Kim. 1982. DO model for discharges from deep impoundments. *Journal of the Environmental Engineering Division, ASCE* 108(EE1):107-122.

Hobbs, C.H., R.J. Byrne, W.R. Kerns, and N.J. Barber. 1981. Shoreline erosion: A problem in environmental management. *Coastal Zone Management Journal* 9(1):89-105.

Hobson, R.D. 1977. *Review of design elements for beach-fill evaluation*. TP 77-6. U.S. Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, VA.

Holland, J.P. 1984. *Parametric investigation of localized mixing in reservoirs*. Technical Report E-84-7. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Original not available for examination. Cited in Price, 1989.

Holler, S. 1989. Buffer strips in watershed management. In, *Watershed Management Strategies for New Jersey*. pp. 69-116., Cook College Department of Environmental Resources and New Jersey Agricultural Experiment Station, Rutgers University, New Brunswick, NJ.

Houston, J.R. 1991. Beachfill performance. *Shore and Beach* 59(3):15-24.

Howington, S.E. 1990. *Simultaneous, Multilevel Withdrawal from a Density Stratified Reservoir*. Technical Report W-90-1. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Hupp, C.R., and A. Simon. 1986. Vegetation and bank-slope development. In *Proceedings of the Forest Federal Interagency Sedimentation Conference*, Las Vegas, NV, pp. 83-92. U.S. Interagency Advisory Committee on Water Data, Washington, DC.

Hupp, C.R., and A. Simon. 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. *Geomorphology* 4:111-124.

Hynson, J.R., P.R. Adamus, J.O. Elmer, T. DeWan, and F.D. Shields. 1985. *Environmental Features for Streamside Levee Projects*. Technical Report E-85-7. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

IECA. 2003. *Impact of Riprap*. International Erosion Control Association. http://www.ieca.org/applications/Discussion/PublicDiscussion.asp?ParentID=429. Accessed September 2005.

International Rivers Network. 2003. *Reviving the World's Rivers: Dam Removal: Technical Challenges*. http://www.irn.org/revival/decom/brochure/rrpt4.html. Accessed June 2003.

Jackson, D. 1989. A glimmer of hope for stream fisheries in Mississippi. *Fisheries* 14:4-9.

Johnson, P.L., and J.F. LaBounty. 1988. *Optimization of Multiple Reservoir Uses Through Reaeration - Lake Casitas, USA: A Case Study.* Commision Internationale des Grands Barrages. Seizieme Congress des Grands Barrages, San Francisco, 1988. Q. 60, R. 27 pp. 437-451.

Jones, R.K., and P.A. March. 1991. Efficiency and cavitation effects of hydroturbine venting. In *Progress in Autoventing Turbine Development*. Tennessee Valley Engineering Authority, Engineering Laboratory, Norris, TN.

Kahler, T., M. Grassley, D. Beauchamp. 2000. *A Summary of the Effects of Bulkheads, Piers, and Other Artificial Structures and Shorezone Development on ESA-listed Salmonids in Lakes*. Washington Cooperative Fish and Wildlife Research Unit. Seattle, Washington. http://www.ci.bellevue.wa.us/departments/Utilities/pdf/dock_bulkhead.pdf. Accessed August 2005.

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser. 1986. *Assessing Biological Integrity in Running Waters: A Method and its Rationale*. Illinois Natural History Survey Special Publication No. 5.

Kaufman, J.H. 1992. Effects on wildlife of restoring the riverine forest in the Rodman Pool area. In *The Case for Restoring the Free-Flowing Ockawah River*. Florida Defenders of the Environment. pp. 38-41. Cited in *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. American Rivers, Washington, D.C.

Killam, G. 2005. *The Clean Water Act Owner's Manual*. 2d ed. River Network, Portland, Oregon.

Knudsen, F.R., P.S. Enger, and O. Sand. 1994. Avoidance responses to low frequency sound in downstream migrating Atlantic salmon smolt, *Salmo salar*. *Journal of Fish Biology*. 45:227-233.

Knutson, P.L. 1988. Role of coastal marshes in energy dissipation and shore protection. In *The Ecology and Management of Wetlands, Volume 1: Ecology of wetlands*, ed. D.D. Hook, W.H. McKee, Jr., H.K. Smith, J. Gregory, V.G. Burrell, Jr.

Kondolf, G.M., G.F. Cada, and M.J. Sale. 1987. Assessing flushing-flow requirements for brown trout spawning gravels in steep streams. *Water Resources Bulletin* 23(5):927-935.

Kondolf, G.M., G.F. Cada, and M.J. Sale. 1987. Assessing flushing-flow requirements for brown trout spawning gravels in steep streams. *Water Resources Bulletin* 23(5): 927-935.

Kraus, N.C., and O.H. Pilkey. 1988. Introduction: The effects of seawalls on the beach. *Journal of Coastal Research* Special Issue No. 4.

Kubecka, J., and J. Vostradovsky. 1995. Effects of dams, regulation and pollution on fish stocks in the Vltava river in Prague. *Regulated Rivers: Research and Management* 10(2-4): 93-98.

Landschoot, P. 1997. *Erosion Control & Conservation Plantings on Noncropland*. Pennsylvania State University, College of Agricultural Sciences, University Park, PA.

Larinier, M. 2000. *Dams and Fish Migration*. Institut de Mecanique des Fluides, Toulouse, France. http://www.dams.org/docs/kbase/contrib/env247.pdf. Accessed June 2003

Lee, M. 1999, March. Costs mount for Snake Dam removal. *Tri-City Herald* http://www.snakedams.com/news/story12.html. Accessed June 2002.

Lewis, B. 1992. *Your Dam - an Asset or a Liability?* Department of Conservation and Natural Resources, Melbourne, Australia. http://www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/access-dams-maintain. Accessed June 2003.

Los Angeles River Watershed. 1973. *Evaluation of check dams for sediment control*. Los Angeles River Watershed, Angeles National Forest, Region 5.

MDEP. 1990. *Best Management Practices for Stormwater Management*. Maine Department of Environmental Protection, Bureau of Water Quality, and York County Soil and Water Conservation District.

Mantell, M.A., S.F. Harper, and L. Propst. 1990. *Creating Successful Communities: A Guidebook to Growth Management Strategies.* Island Press, Washington, DC.

March, P.A., J. Cybularz, and B.G. Ragsdale. 1991. Model tests for evaluation of auto-venting hydroturbines. In *Progress in Autoventing Turbine Development*. Tennessee Valley Authority, Engineering Laboratory, Norris, TN.

Marmulla, G., ed. 2001. *Dams, Fish, and Fisheries: Opportunities, Challenges, and Conflict Resolution*. FAO Fisheries Technical Paper 419. ftp://ftp.fao.org/docrep/fao/004/Y2785E/y2785e.pdf. Accessed April 2004.

MDNR. 2001. *Annual Report 2001: Hydromodification/Channelization*. Maryland Department of Natural Resources, Annapolis, Maryland.

http://www.dnr.state.md.us/bay/czm/nps/publications/2001_annual_report.pdf. Accessed June 2003.

Massachusetts River Restore Program. 2002. *Dam Removal Fact Sheet*. http://www.mass.gov/dfwele/river/pdf/rivdamremove.pdf. Accessed June 2002.

Mathias, M.E., and P. Moyle. 1992. Wetland and aquatic habitats. *Agriculture Ecosystems & Environment* 42(1-2): 165-176.

Mattice, J.S. 1990. Ecological effects of hydropower facilities. In *Hydropower Engineering Handbook*, ed. Gulliver, J.S. and R.E.A. Arndt, pp. 8.1-8.57. McGraw-Hill, New York.

McCully, Patrick. 2001. *Silenced Rivers: The Ecology and Politics of Large Dams*. Zed Books, London.

Meeks, G., Jr. 1990. *State Land Conservation and Growth Management Policy: A Legislator's Guide*. National Conference of State Legislators, Washington, DC.

Merritt, D.M., and D.J. Cooper. 2000. Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River basin, USA. *Regulated Rivers: Research and Management* 16(6): 543-564.

Merz, J.E., J.D., Setka, G.B. Pasternack, and J.M. Wheaton. 2004. Predicting benefits of spawning-habitat rehabilitation to salmonid (*Oncorhynchus* spp.) fry production in a regulated California river. *Canadian Journal of Fisheries and Aquatic Sciences*. 61:1433-1446.

Michigan Sea Grant College Program. 1988. V*egetation and Its Role in Reducing Great Lakes Shoreline Erosion: A Guide for Property Owners*.

Minton, G.R., and A.H. Benedict. 1999. Use of polymers to treat construction site stormwater. In *Proceedings of Conference 30*, International Erosion Control Association, Nashville, TN, February 22–26, 1999, pp. 177–188.

Monk, B., D. Weaver, C. Thompson, and F. Ossiander. 1989. Effects of flow and weir design on the passage behavior of American shad and salmonids in an experimental fish ladder. *North American Journal of Fisheries Management* 9:60-67.

Montgomery Watson. 2001. *Sediment Management Unit 56/57 Demonstration Project, Fox River, Green Bay, Wisconsin*. Prepared for Fox River Group of Companies and Wisconsin Department of Natural Resources.

Morita, K., and S. Yamamoto. 2002. Effects of habitat fragmentation by damming on the persistence of stream-dwelling charr populations. *Conservation Biology* 16(5): 1318-1323.

Muckleston, K.W. 1990. Striking a balance in the Pacific Northwest. *Environment* 32(1): 11-15, 32-35.

Mueller, R.P., D.A. Neitzel, W.V. Mavros, and T.J. Carlson. 1998. *Evaluation of Low and High Frequency Sound for Enhancing Fish Screening Facilities to Protect Outmigrating Salmonids*. Prepared for the U.S. Department of Energy, Bonneville Power Administration. http://www.efw.bpa.gov/Publications/h62611-13.pdf. Accessed August 2005.

Mueller, R.P., D.A. Neitzel, and B.G. Amidan. 1999. *Evaluation of Infrasound and Strobe Lights to Elicit Avoidance Behavior in Juvenile Salmon and Char*. Prepared for the U.S. Department of Energy, Bonneville Power Administration. http://www.pnl.gov/ecology/pubs/PDFs/sound99.pdf. Accessed August 2005.

NAHB. 1995. *Storm water runoff & nonpoint source pollution control guide for builders and developers*. National Association of Home Builders, Washington, DC.

NRC. 1990. *Managing Coastal Erosion*. National Research Council, National Academy Press, Washington, DC.

NRC. 1992. *Restoration of Aquatic Ecosystems.* National Research Council, National Academy Press, Washington, DC.

Negishi, J.N., M. Inoue and M. Nunokawa. 2002. Effects of channelization on stream habitat in relation to spate and flow refugia for macroinvertebrates in northern Japan. *Freshwater Biology* 47 (8): 1515-1529.

Nelson, R.W., J.R. Dwyer, and W.E. Greenberg. 1987. Regulated flushing in a gravel-bed river for channel habitat maintenance: A Trinity River fisheries case study. *Environmental Management* 11(4):479-493.

Nelson, R.W., J.R. Dwyer, and W.E. Greenberg. 1988. *Flushing and Scouring Flows for Habitat Maintenance in Regulated Streams*. Final Technical Report Contract No. 68-01-6986, U.S. Environmental Protection Agency, Criteria and Standard Division, Washington, DC

Nestler, J.M., J. Fritschen, R.T. Milhous, and J. Troxel. 1986a. *Effects of Flow Alterations on Trout, Angling, and Recreation in the Chattahoochee River Between Buford Dam and Peachtree Creek*. Technical Report E-86-10. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Nestler, J.M., C.H. Walburg, J.F. Novotny, K.E. Jacobs, and W.D. Swink. 1986b. *Handbook on Reservoir Releases for Fisheries and Environmental Quality*. Instruction Report E-86-3. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Nichols, F.H., J.E.. Cloern, S.N. Luoma, and D.H. Peterson. 1986. The modification of an estuary. *Science*. 231:567-573.

NOAA. 1995. *National Marine Fisheries Service Releases Draft Biological Opinion to Save Columbia River Basin Salmon*. National Oceanographic and Atmospheric Administration. http://www.publicaffairs.noaa.gov/pr95/jan95/opinion.html. Accessed August 2005.

NOAA. 1998. *Status Review of Chinook Salmon from Washington, Idaho, Oregon, and California*. NOAA Technical Memorandum NMFS-NWFSC-35. http://www.nwfsc.noaa.gov/publications/techmemos/tm35/index.htm. Accessed September 2005.

Oliver, G.G. and L.E. Fidler. 2001. Towards a Water Quality Guidance for Temperature in the Province of British Columbia. Prepared for the Ministry of Environment, Lands, and Parks, British Columbia. Available online at: http://wlapwww.gov.bc.ca/wat/wq/BCguidelines/temptech/index.html. Accessed April 2005.

Oregon Association of Conservation Districts. 2004. *Protecting Streambanks from Erosion: Tips for Small Acreages in Oregon*. http://www.or.nrcs.usda.gov/news/factsheets/fs4.pdf. Accessed March 2004.

Osterkamp, W.R., P. Heilman, and L.J. Lane. 1998. Economic considerations of a continental sediment-monitoring program. *International Journal of Sediment Research* 13(4):12-24.

Office of Technology Assessment, United States Congress (OTA). 1995. *Fish Passage Technologies: Protection at Hydropower Facilities*. OTA-ENV-641. U.S. Government Printing Office, Washington, DC.

Pawlowski, J.T., and L.A. Cook. 1993. Salling Dam drawdown and removal. Unpublished manuscript presented at *The Midwest Regional Technical Seminar on Removal of Dams*, Association of State Dam Safety Officials, 30 September-1 October 1993. Kansas City, MO. Cited in *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. American Rivers, Washington, D.C.

Pennsylvania Fish and Boat Commission. 2001. *Adopt-A-Stream Commission*. http://sites.state.pa.us/PA_Exec/Fish_Boat/jf2001/greathab.htm. Accessed July 2002.

Petersen, J.C. 1990. *Trends and Comparison of Water Quality and Bottom Material of Northern Arkansas, 1974-85 and Effects of Planned Diversions*. USGS Water-Resources Investigation Report 90-4017. U.S. Geological Survey, Little Rock, AR.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. *Rapid Bioassessment Protocols for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish*. EPA/440/4-89/001. U.S. Environmental Protection Agency, Office of Water. Washington, DC. http://www.epa.gov/cgi-bin/claritgw?op-Display&document=clserv:OAR:0555;&rank=4&template=epa. Accessed September 2005.

Pilkey, O.H. 1992. Another view of beachfill performance. *Shore and Beach* 60(2):20-25.

Pilkey, O.H., and H.L. Wright III. 1988. Seawalls versus beaches. *Journal of Coastal Research*, Special Issue No. 4:41-64. Coastal Education and Research Foundation, Charlottesville, VA.

Porter, D.L. 1992. L*ight Touch, Low Cost, Streambank and Shoreline Erosion Control Techniques*. Tennessee Valley Authority.

Pozo, J., E. Orive, H. Fraile, and A. Basaguren. 1997. Effects of Cernadilla-Valparaiso reservoir system in the River Tera. *Regulated Rivers: Research and Management* 13(1): 57-73.

Presumpscot River Plan Steering Committee. 2002. *A Summary of Fisheries Conditions, Issues, and Options for the Presumpcot River*. University of Southern Maine, Casco Bay Estuary Project.
http://www.cascobay.usm.maine.edu/053002_Revised_Fisheries_Short_files/053002_Revised_Fisheries_Short.htm. Accessed September 2005.

Price, R.E. 1989. Evaluating commercially available destratification devices. *Water Operations Technical Support Information Exchange Bulletin*, Volume E-89-2, December 1989. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Pugh, J.R., G.L. Monan, and J.R. Smith. 1971. Effect of water velocity on the fish-guiding efficiency of an electrical guidance system. *Fishery Bulletin* 68(2):307-324.

Rasmussen, Jerry. 1999. *Reservoir and Channelization Projects*. U.S. Fish & Wildlife Service. http://wwwaux.cerc.cr.usgs.gov/MICRA/Reservoirs%20and%20Channelization%20Projects.htm. Accessed April 2004.

Reiser, D.W., M.P. Ramey, and T.R. Lambert. 1985. Review of Flushing Flow in Regulated Streams. Pacific Gas and Electric Company, San Ramon, CA. In *Flushing and Scouring Flows for Habitat Maintenance in Regulated Streams*, ed. W.R. Nelson, J.R. Dwyer, and W.E. Greenberg. 1988. U.S. Environmental Protection Agency, Washington, DC.

River Recovery. 2001. *Why decommission a dam?* http://www.recovery.bcit.ca/dmantle.html. Accessed June 2003.

Roa-Espinosa, A., G.D. Bubenzer, and E.S. Miyashita. No date a. *Sediment and Runoff Control on Construction Sites using Four Application Methods of Polyacryalmide Mix*. Dane County Land Conservation Department, Madison, WI.

Roa-Espinosa, T.B. Wilson, J.M. Normam and K.Johnson. No date b. *Predicting the Impact of Urban Development on Stream Temperature Using a Thermal Urban Runoff Model (TURM).* http://www.epa.gov/owow/nps/natlstormwater03/31Roa.pdf. Accessed September 2005.

Rosgen, D. 1994. A classification of natural rivers. *Catena* 22(3):169-199.

Rosgen, D. 1996. *Applied River Morphology*. Wildland Hydrology, Pagosa Springs, CO.

Roy, D., and D. Messier. 1989. A review of the effects of water transfers - the La Grange hydroelectric complex (Quebec, Canada). *Regulated Rivers: Research and Management* 4:299-316.

Sandheinrich, M.B., and G.J. Atchison. 1986. *Environmental Effects of Dikes and Revetments on Large Riverine Systems*. Prepared by U.S. Fish and Wildlife Service, Iowa Cooperative Fishery Research Unit, and the Department of Animal Ecology, Iowa State University for the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Schueler, T. 1987. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices*. Metropolitan Washington Council of Governments, Washington, DC.

Schueler, T. 1995. *Site Planning for Urban Stream Protection*. Metropolitan Washington Council of Governments, Washington, DC. http://www.cwp.org/SPSP/TOC.htm. Accessed July 2005.

Schueler, T. 1997. Impact of suspended and deposited sediment: risks to the aquatic environment rank high. *Watershed Protection Techniques* 2(3):443–444.

Schulte, Marc., S.M. Forman, D.T. Williams, G. Marshburn, and R. Vermeeren. 2000. *A Stable Channel Design Approach for the Rio Salado, Salt River, Arizona.*

Sherwood, C.R., D.A. Jay, R. Harvey, P. Hamilton, and C. Simenstad. 1990. Historical changes in the Columbia River Estuary. *Progress in Oceanography*, 25:299-352.

Shields, F.D., Jr., A.J. Bowie, and C.M. Cooper. 1995. Control of streambank erosion due to bed degradation with vegetation and structure. *Water Resources Bulletin* 31(3): 475-489.

Shields, F.D., Jr, R.R. Copeland, P.C. Klingeman, M.W. Doyle, and A. Simon. 2003. Design for stream restoration. *Journal of Hydraulic Engineering*, ASCE.

Shields, F.D., Jr., J.J. Hoover, N.R. Nunnally, K.J. Killgore, T.E. Schaefer, and T.N. Waller. 1990. *Hydraulic and Environmental Effects of Channel Stabilization, Twentymile Creek, Mississippi*. EL-90-14. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Shields, F.D., Jr., and T.E. Schaefer. 1990. *ENDOW User's Guide*. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Simon, A. 1989a. A model of channel response in distributed alluvial channels. *Earth Surface Processes and Landforms* 14(1): 11-26.

Simon, A. 1989b. The discharge of sediment in channelized alluvial streams. *Water Resources Bulletin* 25 (6): 1177-1188. American Water Resources Association.

Simon, A., and C.R. Hupp. 1986. Channel evolution in modified Tennessee channels. In *Proceedings of the Forest Federal Interagency Sedimentation Conference*, Las Vegas, NV, pp. 71-82. U.S. Interagency Advisory Committee on Water Data, Washington, DC.

Simon, A., and C.R. Hupp. 1987. Geomorphic and vegetative recovery processes along modified Tennessee streams: An interdisciplinary approach to disturbed fluvial systems. In *Forest Hydrology and Watershed Management*. Proceedings of the Vancouver Symposium, August 1987. IAHS-AISH Publication No. 167.

Simons, D.B., and F. Senturk. 1992. *Sediment Transport Technology*. Water Resources Publication. Littleton, CO.

Smith, D.R., S.C. Wilhelms, J.P. Holland, M.S. Dortch, and J.E. Davis. 1987. *Improved Description of Selective Withdrawal Through Point Sinks*. Technical Report E-87-2. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Smolen, M.D., D.W. Miller, L.C. Wyatt, J. Lichthardt, and A.L. Lanier. 1988. *Erosion and Sediment Control Planning and Design Manual*. North Carolina Sedimentation Control Commission, Raleigh, NC.

Soderberg, R.W. 1995. *Flowing Water Fish Culture*. Lewis Publishers, Boca Raton, LA.

Soil Quality Institute (SQI). 2000. *Soil Quality—Urban Technical Note No. 1: Erosion and Sedimentation on Construction Sites*. http://www.soils.usda.gov/sqi/soil_quality/land_management/urban.html. Accessed June 2003.

Sojka, Robert. 1999. Personal communication. Northwest Irrigation and Soils Research Laboratory. Kimberley, Idaho, May 24, 1999.

Sojka, R.E., and R.D. Lentz, eds. 1996. *Managing irrigation-induced erosion and infiltration with polyacrylamide*. Proceedings from Conference held at College of Southern Idaho, Twin Falls, Idaho. May 6–8, 1996. University of Idaho Miscellaneous Publication No.101-96.

Sotir, R.B. and J.C Fischenich. 2003. *Vegetated Reinforced Soil Slope Streambank Erosion Control*. ERDC TN-EMRRP-SR-30. http://el.erdc.usace.army.mil/elpubs/pdf/sr30.pdf. Accessed October 2004.

Southeastern Wisconsin Regional Planning Commission (SWRPC). 1991. *Costs of Urban Nonpoint Source Water Pollution Control Measures*. Technical Report No. 31.

Stanford and Ward. 1996. A general protocol for restoration of regulated rivers. *Regulated Rivers: Research and Management* 12: 391-413.

Stauble, D.K. 2005. *A Review of the Role of Grain Size in Beach Nourishment Projects*. U.S.

Army Engineer Research and Development Center. Vicksburg, MS. http://www.fsbpa.com/05Proceedings/02-Don%20Stauble.pdf. Accessed August 2005.

Steiger, J., M. James, and F. Gazelle. 1998. Channelization and consequences on floodplain system functioning on the Garonne River, SW France. *Regulated Rivers: Research and Management* 14(1): 13-23.

Stock Seed Farms. No date. *Stock Feed Farms*. http://shop.store.yahoo.com/stockseed/habmixwilcom.html. Accessed April 2004.

Stone and Webster. 1986. *Assessment of Downstream Migrant Fish Protection Technologies for Hydroelectric Application*. Report AP-4711. Palo Alto, California, Electric Power Research Institute.

Stromberg, J.C., and D.T. Patten. 1990. Riparian vegetation instream flow requirements: A case study from a diverted stream in the eastern Sierra Nevada, California, USA. *Environmental Management* 14(2):185-194.

Swanson, S., D. Franzen, and M. Manning. 1987. Rodero Creek: Rising water on the high desert. *Journal of Soil and Water Conservation* 42(6):405-407.

Tachet, J.F. 1997. River incision in south-east France: Morphological phenomena and ecological effects. *Regulated Rivers: Research and Management* 13(1):75-90.

Tainter, S.P. 1982. *Bluff slumping and stability: A consumer's guide*. Michigan Sea Grant, Ann Arbor, MI.

Tanovan, B. 1987. System spill allocation for the control of dissolved gas saturation on the Columbia River. In *Proceedings: CE Workshop on Reservoir Relea*ses. Paper E-87-3. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Misc.

TRB. 2001. *A Process for Setting, Managing, and Monitoring Environmental Windows for Dredging Projects*. Transportation Research Board, Committee for Environmental Windows for Dredging Projects. Washington, DC. http://trb.org/news/blurb_detail.asp?id=556. Accessed August 2005.

TVA. 1985. *Feasibility Report, Tims Ford/Elk River Minimum Flows*. Report Number TVA/ONRED/A&WR-85/22. Tennessee Valley Authority, Office of Natural Resources and Economic Development, Division of Air and Water Resources.

TVA. 1988. *The Tennessee Valley Authority's Nonpoint Source Pollution Control Activities Under the Memorandum of Understanding Between the State of Tennessee and the Tennessee Valley Authority During Fiscal Years 1983-1986*. Tennessee Valley Authority.

TVA. 1990. *Final Environmental Impact Statements, Tennessee River and Reservoir Operation and Planning Review*. Tennessee Valley Authority. Report Number TVA/RDG/EQS-91/1.

Theisen, M. 1996. How to make vegetation stand up under pressure. *Civil Engineering News*.

Theurer, F.D., K.A. Voos, and W.J. Miller. 1984. *Instream Water Temperature Model*. Instream Flow Information Paper No. 16. USDA Fish and Wildlife Service, Cooperative Instream Flow Service Group, Fort Collins, Colorado.

Theurer, F.D., K.A. Voos, and C.G. Prewitt. 1982. Application of IFG's instream water temperature model in the Upper Colorado River. In *Proceedings of the International Symposium on Hydrometeorology*, Denver, CO, 13-17 June 1982, pp. 287-292. American Water Resources Association.

Thornton, K.W., B.L. Kimmel, and F.E. Payne. 1990. *Reservoir Limnology: Ecological Perspectives*. John Wiley & Sons, Inc., New York.

Tommy Silt Fence Machine. No date. *Tommy Silt Fence Machine*. http://www.tommy-sfm.com/pages/tommy/slicing/index.jsp. Accessed April 2004.

Trout Unlimited. n.d. *Small Dams Campaign*. http://www.tu.org/small_dams/about_small_dams.html. Accessed July 2002.

University of Texas. 1998. *Environmental Organic Geochemistry: Course Notes 1998*. http://www.geo.utexas.edu/courses/387e/387e_notes_intro.htm. Accessed October 2004.

USACE. No date. *Spillway Weir*. U.S. Army Corps of Engineers. http://www.nww.usace.army.mil/spillway_weir/default.html. Accessed September 2005.

USACE. 1981a. *Low-cost shore protection, final report on the shoreline erosion control demonstration program (Section 54)*. U.S. Army Corps of Engineers. Washington, DC.

USACE. 1983. *Streambank Protection Guidelines for Landowners and Local Governments*. U.S. Army Corps of Engineers, Vicksburg, MS.

USACE. 1984. *Shoreline Protection Manual*. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 2 vols.

USACE. 1989. *Engineering and Design: Sedimentation Investigations of Rivers and Reservoirs*. U.S. Army Corps of Engineers, Washington, D.C. Engineering Manual No. 1110-2-4000. http://www.usace.army.mil/publications/eng-manuals/em1110-2-4000/toc.htm. Accessed September 2005.

USACE. 1990. *Chesapeake Bay Shoreline Erosion Study: Feasibility Report*. U.S. Army Corps of Engineers.

USACE. 1994. *Channel Stability Assessment for Flood Control Projects*. EM 1110-2-1418. U.S. Army Corps of Engineers, Engineering and Design. http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1418/toc.htm. Accessed April 2005.

USACE. 1997. *To Save the Salmon*. U.S. Army Corps of Engineers, Portland District 11/97. http://www.bluefish.org/tosave.htm. Accessed September 2005.

USACE. 1999. Earthjustice Legal Defense Fund and the Pacific Environmental Advocacy Center vs. U.S. Army Corps of Engineers. U.S. District Court testimony, Seattle.

USACE. 2002a. *River Analysis System: Applications Guide, Example 14: Multiple Culverts*. U.S. Army Corps of Engineers, Hydrologic Engineering Center, CPD-70. http://www.hec.usace.army.mil/software/hec-ras/documents/appguide/cvr_incvr_toc.pdf. Accessed October 2004.

USACE. 2002b. *Columbia River Basin – Dams and Salmon*. U.S. Army Corps of Engineers. http://www.nwd.usace.army.mil/ps/colrvbsn.htm. Accessed August 2005.

USACE. 2003. *Coastal Engineering Manual, Part V*. U.S. Army Corps of Engineers. http://www.usace.army.mil/publications/eng-manuals/em1110-2-1100/PartV/PartV.htm. Accessed December 2004.

USDA–FS. 2002. *A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization*. U.S. Department of Agriculture, Forest Service, FS-683. http://www.fs.fed.us/publications/soil-bio-guide. Accessed October 2004.

USDA-NRCS. 1992. *Engineering Field Handbook, Chapter 18 – Soil Bioengineering for Upland Slope and Protection and Erosion Reduction*. U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.info.usda.gov/CED/ftp/CED/EFH-Ch18.pdf.

USDOE. 1991. *Environmental Mitigation at Hydroelectric Projects, Volume 1: Current Practices for Instream Flow Needs, Dissolved Oxygen, and Fish Passage*. DOE/ID-10360. U.S. Department of Energy.

USDOI. 1988. *Glen Canyon Environmental Studies Final Report*. NTIS No. PB88-183348/AS. U.S. Department of the Interior, Upper Colorado Region, Salt Lake City, UT.

USDOI. 1995. *Final Environmental Impact Statement: Elwha River Ecosystem Restoration, Olympic National Park, Washington*. U.S. Department of the Interior, 647 pp. Cited in *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. American Rivers, Washington, D.C.

USEPA. 1973. *The Control of Pollution from Hydrographic Modifications*. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 1993. *Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters*. EPA 840-B-92-002B. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 1995a. *Ecological Restoration: A Tool to Manage Stream Quality*. EPA 841-F-95-007. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/Ecology. Accessed January 2005.

USEPA. 1995b. *Erosion, Sediment, and Runoff Control for Roads and Highways*. EPA-841-F-95-008d. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/education/runoff.html. Accessed January 2005.

USEPA. 1997a. *Community-Based Environmental Protection: A Resource Book for Protecting Ecosystems and Communities*. EPA 230-B-96-003. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/ecocommunity/tools/resourcebook.htm. Accessed January 2005.

USEPA. 1997b. *Volunteer Stream Monitoring: A Methods Manual*. EPA 841-B-97-003. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/volunteer/stream/stream.pdf. Accessed June 2003.

USEPA. 1998. *National Water Quality Inventory: 1996 Report to Congress*. EPA841-R-97-008. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/305b/96report. Accessed June 2003.

USEPA. 1999. *Storm Water Technology Fact Sheet: Turf Reinforcement Mats*. EPA 832-F-99-002. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2002a. *National Water Quality Inventory: 2000 Report to Congress*. EPA 841-R-02-001. United States Environmental Protection Agency, Washington, DC. http://www.epa.gov/305b/2000report. Accessed June 2003.

USEPA. 2002b. *Environmental Assessment for Proposed Effluent Guidelines and Standards for the Construction and Development Category*. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/guide/construction/envir/C&D_Envir_Assessmt_proposed.pdf. Accessed June 2003.

USEPA. 2002c. *South Myrtle Creek Ditch Project: Removal of Dam Benefits Aquatic Life*. Section 319 Success Stories, Vol. III, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/Section319III/OR.htm. Accessed August 2005.

USEPA. 2003a. *Sediment Oxygen Demand Studies*. U.S. Environmental Protection Agency, New England Regional Laboratory. http://www.epa.gov/region1/lab/ecology/sod.html. Accessed June 2003.

USEPA. 2003b. *National Management Measures to Control Nonpoint Source Pollution from Agriculture*. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/pubs.html. Accessed May 2003.

USEPA. 2003c. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature and Water Quality Standards. EPA 910-B-03-002. U.S. Environmental Protection Agency, Seattle, WA.

USEPA. 2005a. *Watershed Approach Framework*. U.S. Environmental Protection Agency, Washington, DC.
http://www.epa.gov/owow/watershed/framework.html. Accessed August 2005.

USEPA. 2005b. *National Management Measures to Control Nonpoint Source Pollution from Wetlands.* U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/wetmeasures. Accessed September 2005.

USEPA. 2005c. *Draft Handbook for Developing Watershed Plans to Restore and Protect Our Waters*. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/nps.

USEPA. 2005d. *National Management Measures to Control Nonpoint Source Pollution from Urban Areas*. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/urbanmm/index.html. Accessed May 2003.

USEPA. 2005e. *Draft National Management Measures to Control Nonpoint Source Pollution from Forestry*. U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/owow/nps/forestrymgmt. Accessed October 2004.

USFWS. 2001. *Gas Supersaturation Monitoring Report for Spill Below Bonneville Dam: March 10-13, 2001*. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA.
http://www.fws.gov/pacific/columbiariver/pdfdocs/water/2001%20GBT%20Report.pdf. Accessed September 2005.

USGS. 1997. *Sediment Oxygen Demand in the Tualatin River Basin, Oregon, 1992-96*. U.S. Geological Society, Stewart Rounds and Micelis Doyle. http://or.water.usgs.gov/pubs_dir/Html/WRIR97-4103/contents.html. Accessed October 2004.

van der Borg, R., and J. Ferguson. 1989. Hydropower and fish passage impacts. In *Proceedings Waterpower '89,* American Society of Civil Engineers, Niagara Falls, NY, August 23-25, 1989.

VanderKooy, S.J. and M.S. Peterson. 1998. Critical current speed for young Gulf Coast walleyes. *Transactions of the American Fisheries Society* 127(1):137-140.

Van Holmes, C., and J. Anderson. 2004. *Predicted Fall Chinook Survival and Passage Timing Under BiOp and Alternative Summer Spill Programs Using the Columbia River Salmon Passage*

Model. Columbia Basin Research, University of Washington. http://www.cbr.washington.edu/papers/2004SummerSpill.pdf. Accessed September 2005.

Waldrop, W.R. 1992. The autoventing turbine, a new generation of environmentally improved hydroturbines. In *Proceedings of the American Power Conference*.

Walker, R. and Snodgrass, W. 1986. Model for sediment oxygen demand in lakes. *Journal of Environmental Engineering*, v. 112, no. 1, p. 25-43.

Wang, W., 1980. Fractionation of sediment oxygen demand. *Water Research*, v. 14, p. 603-612.

Washington State Department of Ecology. 1989. *Nonpoint source pollution assessment and management program*. Document No. 88-17. Washington State Department of Ecology, Water Quality Program, Olympia, WA. http://www.ecy.wa.gov/biblio/981813wr.html. Accessed June 2003.

Washington Department of Fish and Wildlife (WDFW), Washington Department of Transportation, and Washington Department of Ecology. 2003. *Integrated Streambank Protection Guidelines*. Washington State Aquatic Habitat Guidelines Program. http://www.wdfw.wa.gov/hab/ahg/ispgdoc.htm. Accessed October 2004.

Watson, C.C., D.S. Biedenharn, and S.H. Scott. 1999. *Channel Rehabilitation: Process, Design, and Implementation*. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. http://chl.erdc.usace.army.mil/Media/2/9/0/ChannelRehabilitation.pdf. Accessed August 2005.

WEF. 1997. *The Clean Water Act Desk Reference: 25th Anniversary Edition*. Water Environment Federation, Alexandria, VA.

WEF. 2003. *Glossary of Water Environment Terms*. Water Environment Federation. http://www.wef.org/publicinfo/newsroom/wastewater_glossary.jhtml#s. Accessed August 2005.

WRM. 2000. *Dam Repair or Removal: A Decision-Making Guide*. Water Resources Management Practicum. http://www.ies.wisc.edu/research/wrm00. Accessed May 2003.

Watson, C.C., D.S. Biedenharn, and S.H. Scott. 1999. *Channel rehabilitation: processes, design, and implementation*. United States Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Welsch, J.D. No date. *Riparian Forest Buffers: Function and Design for Protection and Enhancement of Water Resources*. U.S. Department of Agriculture Forest Service, Northeastern Area State and Private Forestry, Randnor, PA.

Wesche, T.A., V.R. Hasfurther, and Q.D. Skinner. 1987. Recommendation and evaluation of a mitigative flushing flow region below a high mountain diversion. In *Proceedings of the*

Symposium on Water Resources Related to Mining and Energy-Preparing for the Future, American Water Resources Association, Bethesda, MD. pp. 281-298.

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*. Academic Press. San Diego, CA.

Wilhelms, S.C. 1984. Turbine venting. *Environmental & water quality operational studies*, Volume E-84-5, September 1984. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Wilhelms, S.C. 1988. Reaeration at low-head gated structures; preliminary results. *Water operations technical support*, Volume E-88-1, July 1988. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Wilhelms, S.C., and D. R. Smith. 1981. *Reaeration through gated-conduit outlet works*. Technical Report E-81-5. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Technical Report E-81-5.

Wilhelms, S.C. and L.I. Yates. 1995. Improvement of reservoir releases by aeration. *Water Quality Technical Note MS-01*. U.S. Army Corps of Engineers, Vicksburg, MS.

Woodhouse, W.W., Jr. 1978. *Dune Building and Stabilization with Vegetation*. Special Report No. 3. U.S. Army Corps of Engineers Coastal Engineering Center, Fort Belvoir, VA.

Wunderlich, R.C., B.D. Winter, and J.H. Meyer. 1994. Restoration of the Elwha River ecosystem and anadromous fisheries. *Salmon Ecosystem Restoration: Myth and Reality*. Proceedings of the 1994 Northeast Pacific Chinook and Coho Salmon Workshop. American Fisheries Society, Corvalis, OR.

Wyzga, B. 2001. Impact of channelization-induced incision of the Skawa and Wisloka rivers, southern Poland, on the condition of overbank deposition. *Regulated Rivers: Research and Management* 17(1): 85-100.

Zimmerman, M.J., and M. S. Dortch. 1989. Modelling water quality of a reregulated stream below a hydropower dam. *Regulated Rivers: Research and Management* 4:235-247.

Resources

Documents

Abbe, T.B., D.R. Montgomery, and C. Petroff. 1997. Design of stable in-channel wood debris structures for bank protection and habitat restoration: an example from the Cowlitz River, WA. In *Proceedings of the Conference on Management of Landscape Disturbed by Channel Incision*, May 19-23, 1997.

Abt, S.R. 1995. Settlement and submergence adjustments for Parshall flume. *Journal of Irrigation Drainage Engineering, American Society of Civil Engineers* 121(5): 317-321.

Adams, W.J., R.A. Kimerle, and J. W. Barnett, Jr. 1992. Sediment quality and aquatic life assessment. *Environmental Science and Technology* 26(10): 1864-1875.

Adamus, P.R. 1993. *Irrigated Wetlands of the Colorado Plateau: Information Synthesis and Habitat Evaluation Method*. EPA 600-R-93-071, U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Allan, J.D. 1995. *Stream Ecology—Structure and Function of Running Waters*. Chapman and Hall, New York.

Allen, H.H. and J.R. Leech. 1997. *Bioengineering for Streambank Erosion Control: Report 1 Guidelines*. U.S. Army Corps of Engineers, Environmental Impact Research Program, Technical Report EL-97-8. http://el.erdc.usace.army.mil/elpubs/pdf/trel97-8.pdf. Accessed October 2004.

Alonso, C.V., F.D. Theurer, and D.W. Zachmann. 1996. *Sediment Intrusion and Dissolved Oxygen Transport Model—SIDO*. Technical Report No. 5. USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi.

American Rivers. No date. *Ten Reasons Why Dams Damage Rivers*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=759. Accessed October 2004.

American Rivers. 2000. *Paying for Dam Removal: A Guide to Selected Funding Sources*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1729. Accessed October 2004.

American Rivers. 2004. *Beyond Dams: Options and Alternatives*. http://www.amrivers.org/doc_repository/DamRemoval/BeyondDamsOptionsandAlternative.pdf. Accessed October 2004.

ASCE. 1997. *Guidelines for the Retirement of Hydroelectric Facilities*. American Society of Civil Engineers.

ASCE. 1998. River width adjustment, I: processes and mechanisms. American Society of Civil Engineers. *Journal of Hydraulic Engineering* 124: 881-902.

ASCE. 1998. River width adjustment, II: modeling. American Society of Civil Engineers. *Journal of Hydraulic Engineering* 124: 903-917.

APHA. 1998. *Standard Methods for the Examination of Water and Wastewater*, 20th ed., ed. L.S. Clesceri, A.E. Greenberg, and A.D. Eaton. American Public Health Association, Washington, DC.

Arcement, G.J., Jr., and V.R. Schneider. 1984. *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*. Federal Highway Administration Technical Report No. FHWA-TS-4-204. U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

Armour, C.L. and S.C. Williamson. 1988. *Guidance for Modeling Causes and Effects in Environmental Problem Solving*. U.S. Fish and Wildlife Service Biological Report 89(4).

Armour, C.L., and J.G. Taylor. 1991. Evaluation of the Instream Flow Incremental Methodology by U.S. Fish and Wildlife Service field users. *Fisheries* 16(5).

Ashmore, P.E., T.R. Yuzyk, and R. Herrington. 1988. *Bed-Material Sampling in Sandbed Streams*. Environment Canada Report IWD-HQ-WRB-SS-88-4. Environment Canada, Inland Waters Directorate, Water Resources Branch, Sediment Survey Section.

Atkins, J.B., and J.L. Pearman. 1994. *Low-Flow and Flow-Duration Characteristics of Alabama Streams*. U.S. Geological Survey Water-Resources Investigations Report 93-4186. U.S. Geological Survey.

Averett, R.C. and L.J. Schroder. 1993. *A Guide to the Design of Surface-Water-Quality Studies*. U.S. Geological Survey Open-File Report 93-105. U.S. Geological Survey.

Barinaga, M. 1996. A recipe for river recovery? *Science* 273: 1648-1650.

Bartholow, J.M., J.L. Laake, C.B. Stalnaker, S.C. Williamson. 1993. A salmonid population model with emphasis on habitat limitations. *Rivers* 4: 265-279.

Bathurst, J.C. 1985. *Literature Review of Some Aspects of Gravel-Bed Rivers*. Institute of Hydrology, Wallingford, Oxfordshire, U.K.

Bayley, P.B. and H.W. Li. 1992. Riverine fishes. In *The Rivers Handbook*, ed. P. Calow and G.E. Petts, Blackwell Scientific Publications, vol. 1, pp. 251-281. Oxford, U.K.

Bayley, P.B. 1995. Understanding large river-floodplain ecosystems. *BioScience* 45(3): 154.

Behmer, D.J., and C.P. Hawkins. 1986. Effects of overhead canopy on macroinvertebrate production in a Utah stream. *Freshwater Biology* 16(3): 287-300.

Belt, G.H., J. O'Laughlin, and T. Merrill. 1992. *Design of Forest Riparian Buffer Strips for the Protection of Water Quality: Analysis of Scientific Literature*. Report No. 8. Idaho Forest, Wildlife and Range Policy Analysis Group, Idaho Forest, Wildlife and Range Experiment Station, Moscow, Idaho.

Beschta, R.L., W.S. Platts, J.B. Kauffman, and M.T. Hill. 1994. Artificial stream restoration—money well spent or an expensive failure? In *Proceedings on Environmental Restoration*, Universities Council on Water Resources 1994 Annual Meeting, August 2-5, Big Sky, Montana, pp. 76-104.

Biedenharn, D.S., and C.R. Thorne. 1994. Magnitude-frequency analysis of sediment transport in the Lower Mississippi River. Regulated Rivers: *Research and Management* 9(4): 237-251.

Bio West. 1995. *Stream Habitat Improvement Evaluation Project*. Bio West, Logan, Utah.

Bisson, R.A., R.E. Bilby, M.D. Bryant, C.A. Dolloff, G.B. Grette, R.A. House, M.J. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In *Streamside Management: Forestry and Fishery Interactions,* ed. E.O. Salo and T.W. Cundy, pp. 143-190. Institute of Forest Resources, University of Washington, Seattle, Washington.

Booth, D., D. Montgomery, and J. Bethel. 1996. Large woody debris in the urban streams of the Pacific Northwest. In *Effects of Watershed Development and Management on Aquatic Systems,* ed. L. Rosner, Proceedings of Engineering Foundation Conference, Snowbird, Utah, August 4-9, pp. 178-197.

Booth, D. and C. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection and the limits of mitigation. *Journal of the American Water Resources Association* 33(5): 1077-1089.

Bourassa, N. and A. Morin. 1995. Relationships between size structure of invertebrate assemblages and trophy and substrate composition in streams. *Journal of the North American Benthological Society*. 14: 393-403.

Bovee, K.D., T.J. Newcomb, and T.J. Coon. 1994. *Relations between habitat variability and population dynamics of bass in the Huron River, Michigan*. National Biological Survey Biological Report 22. National Biological Survey.

Bowie, G. L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W. H. Chan, and S.A. Gherini. 1985. *Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling,* 2d ed. EPA 600-3-85-040. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Briggs, J.C. 1986. Introduction to the zoogeography of North American fishes. In *Zoogeography of North American Freshwater Fishes*, ed. C.H. Hocutt and E.O. Wiley, pp. 1-16. Wiley Interscience, New York.

Briggs, M.K., B.A. Roundy, and W.W. Shaw. 1994. Trial and error—assessing the effectiveness of riparian revegetation in Arizona. *Restoration and Management Notes* 12(2): 160-167.

Brinson, M. 1995. *The HGM Approach Explained*. National Wetlands Newsletter, November-December 1995: 7-13.

Brinson, M.M., F.R. Hauer, L.C. Lee, W.L. Nutter, R.D. Rheinhardt, R.D. Smith, and D. Whigham. 1995. *A Guidebook for Application of Hydrogeomorphic Assessments to Riverine Wetlands*. Technical Report WRP-DE-11. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Brookes, A. 1995. The importance of high flows for riverine environments. In *The Ecological Basis for River Management*, ed. D.M. Harper and A.J.D. Ferguson. John Wiley and Sons, Ltd., Chichester, U.K.

Brooks, R.P., E.D. Bellis, C.S. Keener, M.J. Croonquist, and D.E. Arnold. 1991. A methodology for biological monitoring of cumulative impacts on wetland, stream, and riparian components of watershed. In *Proceedings of an International Symposium: Wetlands and River Corridor Management*, July 5-9, 1989, Charleston, South Carolina, ed. J.A. Kusler and S. Daly, pp. 387-398.

Brownlie, W.R. 1981. *Prediction of Flow Depth and Sediment Discharge in Open Channels*. Report No. KH-R-43A. California Institute of Technology, W.M. Keck Laboratory of Hydraulics and Water Resources, Pasadena.

Bryant, M.D. 1995. Pulsed monitoring for watershed and stream restoration. *Fisheries* 20(11):6-13.

Center for Watershed Protection. 1995. *Watershed Protection Techniques*, vol. 1, no. 4. Center for Watershed Protection, Silver Spring, Maryland.

Chaney, E., W. Elmore, and W.S. Platts. 1990. *Livestock Grazing on Western Riparian Areas*. U.S. Environmental Protection Agency, Region 8.

Chang, H.H. 1988. *Fluvial Processes in River Engineering*. John Wiley and Sons, Ltd., New York.

Chang, H.H. 1990. *Generalized Computer Program FLUVIAL-12, Mathematical Model for Erodible Channels, User's Manual*. April.

Cole, G.A. 1994. *Textbook of Limnology*, 4th ed. Waveland Press, Prospect Heights, Illinois.

Collier, M., R.H. Webb, and J.C. Schmidt. 1996. *Dams and Rivers: A Primer on the Downstream Effects of Dams*. U.S. Geological Survey Circular vol. 1126 (June).

Conroy, S. D. and T. J. Svejcar. 1991. Willow planting success as influenced by site factors and cattle grazing in northeastern California. *Journal of Range Management* 44 (1): 59-63.

Cooke, G.D., E.B. Welch, S.A. Peterson, and P.R. Newroth. 1993. *Restoration and Management of Lakes and Reservoirs*. 2nd ed. Lewis Publishers, Boca Raton, FL.

Cooper, A.C. 1965. The effect of transported stream sediments on survival of sockeye and pink salmon eggs and alevin. *Int. Pac. Salmon Fish. Comm.*, Bulletin No. 18.

Cooper, C.M. and S.S. Knight. 1987. Fisheries in man-made pools below grade-control structures and in naturally occurring scour holes of unstable streams. *Journal of Soil and Water Conservation* 42(5): 370-373.

Copeland, R.R. 1994. *Application of Channel Stability Methods—Case Studies*. Technical Report HL-94-11, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Coppin, N.J. and I.G. Richards. 1990. *Use of Vegetation in Civil Engineering*. Construction Industry Research and Information Association (CIRIA), London. ISBN 0-408-03849-7.

Couch, C. 1997. Fish dynamics in urban streams near Atlanta, Georgia. Technical Note 94. *Watershed Protection Techniques* 2(4):511-514.

Covich, A.P. 1993. Water and ecosystems. In *Water in Crisis: A Guide to the World's Freshwater Resources*, ed. P.H. Gleick. Oxford University Press, Oxford, United Kingdom.

Darby, S.E. and C.R. Thorne. 1996. Numerical simulation of widening and bed deformation of straight sand-bed rivers. *Journal of Hydraulic Engineering* 122:184-193. ISSN 0733-9429.

Darby, S.E. and C.R. Thorne. 1992. *Approaches to Modeling Width Adjustment in Curved Alluvial Channels*. Working Paper 20, Department of Geography, University of Nottingham, U.K.

Department of the Interior, Department of Commerce, and Lower Elwha S'Klallam Tribe. 1994. *The Elwha Report: Restoration of the Elwha River Ecosystem and Native Anadromous Fisheries*. U.S. Government Printing Office 1994-590-269.

Dirr, M.A. and C.W. Heuser. 1987. *The Reference Manual of Woody Plant Propagation*. Varsity Press, Athens, Georgia.

Dissmeyer, G.E. 1994. *Evaluating the Effectiveness of Forestry Best Management Practices in Meeting Water Quality Goals or Standards*. USDA Forest Service Miscellaneous Publication 1520, Southern Region, Atlanta, Georgia.

Downs, P.W. 1995. River channel classification for channel management purposes. In *Changing River Channels*, ed. A. Gurnell and G. Petts. John Wiley and Sons, Ltd., New York.

Dramstad, W.E., J.D. Olson, and R.T. Gorman. 1996. *Landscape Ecology Principles in Landscape Architecture and Land-Use Planning*. Island Press, Washington, DC.

Dunster, J. and K. Dunster. 1996. *Dictionary of Natural Resource Management*. University of British Columbia. April. ISBN: 077480503X.

EPRI. 1996. *EPRI's CompMech Suite of Modeling Tools Population-level Impact Assessment*. Publication WO3221. Electric Power Research Institute, Palo Alto, California.

Elmore, W. and J.B. Kauffman. 1994. Riparian and watershed systems: degradation and restoration. In *Ecological Implications of Livestock Herbivory in the West*, ed. M. Vavra, W.A. Laycock, and R.D. Piper, pp. 211-232. Society for Range Management, Denver, CO.

Erman, N.A. 1991. Aquatic invertebrates as indicators of biodiversity. In *Proceedings of a Symposium on Biodiversity of Northwestern California, Santa Rosa, California*. University of California, Berkeley.

Fan, S.S., ed. 1988. Twelve selected computer stream sedimentation models developed in the United States. In *Proceedings of the Interagency Symposium on Computer Stream Sedimentation Models, Denver, CO, October 1988*. Federal Energy Regulatory Commission, Washington, DC.

Fan, S.S. and B.C. Yen, eds. 1993. *Report on the Second Bilateral Workshop on Understanding Sedimentation Processes and Model Evaluation, San Francisco, CA, July 1993*. Proceedings published by the Federal Energy Regulatory Commission, Washington, DC.

Federal Interagency Sedimentation Project. 1986. *Catalog of Instruments and Reports for Fluvial Sediment Investigations*. Federal Inter-Agency Sedimentation Project, Minneapolis, Minnesota.

FEMA. 1994. *A Unified National Program for Floodplain Management. Federal Interagency Floodplain Management Task Force, Washington, D.C.* Federal Emergency Management Agency

FEMA. 1994. *Protecting Floodplain Resources: a Guidebook for Communities*. Federal Emergency Management Agency, Federal Interagency Floodplain Management Task Force, Washington, D.C.

FERC. 1996. *Reservoir Release Requirements for Fish at the New Don Pedro Project, California*. Federal Energy Regulatory Commission. Final Environmental Impact Statement. Office of Hydropower Licensing, FERC-EIS-0081F.

FISRWG. 1998. *Stream Corridor Restoration Principles, Processes, and Practices*. Federal Interagency Stream Restoration Working Group. http://www.nrcs.usda.gov/technical/stream_restoration. Accessed October 2004.

Ferguson, B.K. 1991. Urban stream reclamation. *Journal of Soil and Water Conservation* 46(5): 324-328.

Fischenich, C. 2000. *Glossary of Stream Restoration Terms*. http://el.erdc.usace.army.mil/elpubs/pdf/sr01.pdf. Accessed October 2004.

Fischenich, J. C. and Allen, H. 2000. *Stream Management*. ERDC/EL SR-W-00-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://el.erdc.usace.army.mil/elpubs/pdf/srw00-1/srw00-1.pdf. Accessed October 2004.

Flosi, G. and F.L. Reynolds. 1994. *California Salmonid Stream Habitat Restoration Manual*. 2nd ed. California Department of Fish and Game, Sacramento.

Fogg, J.L. 1995. *River Channel Restoration: Guiding Principles for Sustainable Projects*, ed. A. Brookes and F.D. Shields. John Wiley and Sons. ISBN: 0471961396.

Forman, R.T.T. and M. Godron. 1986. *Landscape Ecology*. John Wiley and Sons, New York.

Forman, R.T.T. 1995. *Land Mosaics: the Ecology of Landscapes and Regions*. Cambridge University Press, Great Britain.

Francfort, J.E., G.F. Cada, D.D. Dauble, R.T. Hunt, D.W. Jones, B.N. Rinehart, G.L. Sommers, and R.J. Costello. 1994. *Environmental Mitigation at Hydroelectric Projects, vol. II.* Benefits and Costs of Fish Passage and Protection. DOE/ID-10360(V2). Prepared for U.S. Department of Energy, Idaho Operations Office by Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho.

Fredrickson, L.H. and T.S. Taylor. 1982. *Management of Seasonally Flooded Impoundments for Wildlife*. U.S. Fish and Wildlife Service Resource Publication 148. U.S. Fish and Wildlife Service.

French, R.H. 1985. *Open-channel Hydraulics*. McGraw-Hill Publishing Co., New York.

Friedman, J.M., M.L. Scott, and W.M. Lewis, Jr. 1995. Restoration of riparian forests using irrigation, disturbance, and natural seedfall. *Environmental Management* 19:547-557.

Frissell, C.A., W.L. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchial framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management* 10:199-214.

Galli, J. 1991. *Thermal Impacts Associated with Urbanization and Stormwater Best Management Practices*. Metropolitan Washington Council of Governments, Maryland Department of Environment, Washington, DC.

Garcia de Jalon, D. 1995. Management of physical habitat for fish stocks. In *The Ecological Basis for River Management*, ed. D.M. Harper and J.D. Ferguson, pp. 363-374. John Wiley & Sons, Chichester.

Garcia, M.H., L. Bittner, and Y. Nino. 1994. *Mathematical Modeling of Meandering Streams in Illinois: a Tool for Stream Management and Engineering*. Civil Engineering Studies, Hydraulic Engineering Series No. 43, University of Illinois, Urbana.

Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. VanNostrand Reinhold, New York.

Goldman, S.J., K. Jackson, and T.A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. McGraw Hill Book Company, New York.

Gomez, B. and M. Church. 1989. An assessment of bedload transport formulae for gravel bed rivers. *Water Resources Research* 25(6): 1161-1186.

Gordon, N.D., T.A. McMahon, and B.L. Finlayson. 1992. *Stream Hydrology: an Introduction for Ecologists*. John Wiley & Sons, Chichester, U.K.

Gore, J.A. and F.D. Shields, Jr. 1995. Can large rivers be restored? *BioScience* 45:142-152.

Grant, G.E., F.J. Swanson, and M.G. Wolman. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. *Geological Survey of America Bulletin* 102:340-352.

Gregory, K., R. Davis, and P. Downs. 1992. Identification of river channel change due to urbanization. *Applied Geography* 12:299-318.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective on riparian zones. *Bioscience* 41:540-551.

Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. *Design Hydrology and Sedimentation for Small Catchments*. Academic Press, San Diego.

Hackney, C.T., S.M. Adams, and W.H. Martin, eds. 1992. *Biodiversity of the Southeastern United States: Aquatic Communities*. John Wiley and Sons, New York.

Hammitt, W.E. and D.N. Cole. 1987. *Wildland Recreation: Ecology and Management*. John Wiley and Sons, New York.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. *Stream Channel Reference Sites: an Illustrated Guide to Field Technique*. General Report No. RM-245. U.S. Department of Agriculture, Forest Service, Fort Collins, Colorado.

Hart, D.D. and N.L. Poff. 2002. A special section on dam removal and river restoration. *BioScience* 52: 653-655.

Hartmann, H. and D.E. Kester. 1983. *Plant Propagation: Principles and Practice*. Prentice-Hall, Englewood Cliffs, New Jersey.

Heiner, B.A. 1991. Hydraulic analysis and modeling of fish habitat structures. *American Fisheries Society Symposium* 10: 78-87.

Helwig, P.C. 1987. Canal design by armoring process. In *Sediment Transport in Gravel-bed Rivers*, ed. C.R. Thorne, J.C. Bathurst, and R.D. Hey. John Wiley and Sons, Ltd., New York.

Hemphill, R.W. and M.E. Bramley 1989. *Protection of River and Canal Banks*. Construction Industry Research and Information Association/Butterworths, London.

Hey, R.D. 1990. *Design of Flood Alleviation Schemes: Engineering and the Environment*. School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom.

Hey, R.D. 1994. Restoration of gravel-bed rivers: principles and practice. In *"Natural" Channel Design: Perspectives and Practice*, ed. D. Shrubsole, pp. 157-173. Canadian Water Resources Association, Cambridge, Ontario.

Hey, R.D. 1995. River processes and management. In *Environmental Science for Environmental Management*, ed. T. O'Riordan, pp. 131-150. Longman Group Limited, Essex, U.K., and John Wiley, New York.

Hey, R.D., and C.R. Thorne. 1986. Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering* 112(8): 671-689.

Hoag, J.C. 1992. Planting techniques from the Aberdeen, ID, plant materials center for vegetating shorelines and riparian areas. In *Symposium on Ecology and Management of Riparian Shrub Communities*, USDA Forest Service General Technical Report INT-289, pp. 165-166.

Hoffman, C.H. and B.D. Winter. 1996. Restoring aquatic environments: a case study of the Elwha River. In *National Parks and Protected Areas: Their Role in Environmental Protection*, ed. R.G. Wright, pp. 303- 323. Blackwell Science, Cambridge.

Holdren, C., W. Jones, and J. Taggart. 2001. *Managing Lakes and Reservoirs*. North American Lake Management Society and Terrene Institute, in cooperation with the Office of Water, Assessment and Watershed Protection Division, U.S. Environmental Protection Agency, Madison, WI.

Holly, M.F. Jr., J.C. Yang, P. Schwarz, J. Schaefer, S.H. Su, and R. Einhelling. 1990. *CHARIMA – Numerical Simulation of Unsteady Water and Sediment Movement in Multiply Connected Network of Mobile-bed Channels*. IIHR Report No. 343. Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City.

Holmes, N. 1991. *Post-project Appraisal of Conservation Enhancements of Flood Defense Works*. Research and Development Report 285/1/A. National Rivers Authority, Reading, U.K.

Horwitz, A.J., C.R. Demas, K.K. Fitzgerald, T.L. Miller, and D.A. Rickert. 1994. *U.S. Geological Survey Protocol for the Collection and Processing of Surface-water Samples for the Subsequent Determination of Inorganic Constituents in Filtered Water*. U.S. Geological Survey Open-File Report 94-539.

Hunter, C.J. 1991. *Better Trout Habitat: a Guide to Stream Restoration and Management*. Island Press. November. ISBN: 0933280777.

Interagency Ecosystem Management Task Force. 1995. *The Ecosystem Approach: Healthy Ecosystems and Sustainable Economies*, vol. I, Overview. Council on Environmental Quality, Washington, DC.

Jacoby, P.W. 1987. *Chemical Control*. Vegetative Rehabilitation and Equipment Workshop, 41st Annual Report. U.S. Forest Service, Boise, Idaho.

Jager, H.I., D.L. DeAngelis, M.J. Sale, W. Van Winkle, D.D. Schmoyer, M.J. Sabo, D.J. Orth, and J.A. Lukas. 1993. An individual-based model for smallmouth bass reproduction and young-of-year dynamics in streams. *Rivers* 4: 91-113.

Java, B.J. and R.L. Everett. 1992. Rooting hardwood cuttings of Sitka and thinleaf alder. In *Symposium on Ecology and Management of Riparian Shrub Communities*, USDA Forest Service General Technical Report INT-289, U.S. Department of Agriculture, Forest Service, pp. 138-141.

Jennings, M.E., W.O. Thomas, Jr., and H.C. Riggs. 1994. *Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungauged Sites 1993*. U.S. Geological Survey Water-Resources Investigations Report 94-4002. U.S. Geological Survey.

Jensen, M.E., R.D. Burmand, and R.G. Allen, eds. 1990. Evapotranspiration and irrigation water requirements. *American Society of Civil Engineers*.

Johannesson, H. and G. Parker. 1985. *Computer Simulated Migration of Meandering Rivers in Minnesota*. Project Report No. 242. St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Johnson, A.W. and J.M. Stypula, eds. 1993. *Guidelines for Bank Stabilization Projects in Riverine Environments of King County*. King County Department of Public Works, Surface Water Management Division, Seattle, Washington.

Johnson, R.R. and C.H. Lowe. 1985. On the development of riparian ecology. In *Riparian Ecosystems and Their Management: Reconciling Conflicting Uses*, tech coords. R.R. Johnson et al., pp. 112- 116. USDA Forest Service General Technical Report RM-120. Rocky Mountain Forestry and Range Experimental Station, Fort Collins, Colorado.

Johnson, W.C. 1994. Woodland expansion in the Platte River, Nebraska: patterns and causes. *Ecological Monographs* 64: 45-84.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. In *Proceedings of the International Large River Symposium*, ed. D.P. Dodge, *Can. Spec. Publ. Fish. Aquat. Sci.* 106, pp. 110-127.

Karle, K.F. and R.V. Densmore. 1994. Stream and riparian floodplain restoration in a riparian ecosystem disturbed by placer mining. *Ecological Engineering* 3:121-133.

Kansas State Conservation Commission. No date. *Kansas River and Stream Corridor Management Guide*. Edited by Phil Balch, State Conservation Commission.

Karr, J.R. and W. Chu. 1997. *Biological Monitoring and Assessment: Using Multimetric Indexes Effectively*. EPA 235-R97-001. University of Washington, Seattle.

Kauffman, J.B., R.L. Beschta, and W.S. Platts. 1993. *Fish Habitat Improvement Projects in the Fifteenmile Creek and Trout Creek Basins of Central Oregon: Field Review and Management Recommendations*. U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Kentula, M.E., R.E. Brooks, S.E. Gwin, C.C. Holland, A.D. Sherman, and J.C. Sinfeos. 1992. *An Approach to Improving Decision Making in Wetland Restoration and Creation*. Island Press, Washington, DC.

Kerchner, J.L. 1997. Setting riparian/aquatic restoration objectives within a watershed context. *Restoration Ecology* 5(45).

Kern, K. 1992. Restoration of lowland rivers: the German experience. In *Lowland Floodplain Rivers: Geomorphological Perspectives*, ed. P.A. Carling and G.E. Petts, pp. 279-297. John Wiley and Sons, Ltd., Chichester, U.K.

King, R. 1987. Designing plans for constructibility. *Journal of Construction and Management* 113:1-5.

Klemm, D. J., P.A. Lewis, F. Fulk, and J. M. Lazorchak. 1990. *Macroinvertebrate Field and Laboratory Methods for Evaluating the Biological Integrity of Surface Waters*. EPA/600/4-90-030. Environmental Monitoring Systems Laboratory, Cincinnati, Ohio.

Klimas, C.V. 1991. Limitations on ecosystem function in the forested corridor along the lower Mississippi River. In *Proceedings of the International Symposium on Wetlands and River Corridor Management*, Association of State Wetland Managers, Berne, New York, pp. 61-66.

Klimas, C.V. 1987. River regulation effects on floodplain hydrology and ecology. In *The Ecology and Management of Wetlands*, Chapter IV, ed. D. Hook et al. Croom Helm, London.

Knopf, F.L., R.R. Johnson, T. Rich, F.B. Samson, and R.C. Szaro. 1988. Conservation of riparian systems in the United States. *Wilson Bulletin* 100: 272-284.

Knopf, F.L. 1986. Changing landscapes and the cosmopolitanism of the eastern Colorado avifauna. *Wildlife Society Bulletin* 14: 132-142.

Knott, J.M., C.J. Sholar, and W.J. Matthes. 1992. *Quality Assurance Guidelines for the Analysis of Sediment Concentration by the U.S. Geological Survey Sediment Laboratories*. U.S. Geological Survey Open-File Report 92-33. U.S. Geological Survey.

Knott, J.M., G.D. Glysson, B.A. Malo, and L.J. Schroder. 1993. *Quality Assurance Plan for the Collection and Processing of Sediment Data by the U.S. Geological Survey, Water Resources Division*. U.S. Geological Survey Open-File Report 92-499. U.S. Geological Survey.

Knutson, P.L., and M.R. Inskeep. 1982. *Shore Erosion Control with Salt Marsh Vegetation*. Coastal Engineering Technical Aid No. 82-3. U.S. Army Corps of Engineers Coastal Engineering Research Center, Vicksburg, MS.

Knutson, P.L. 1977. *Planting Guidelines for Marsh Development and Bank Stabilization*. U.S. Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, VA. Coastal Engineering Technical Aid No. 77-3.

Kohler, C.C., and W.A. Hubert. 1993. *Inland Fisheries Management in North America*. American Fisheries Society, Bethesda. Maryland.

Kondolf, G.M., and E.R. Micheli. 1995. Evaluating stream restoration projects. *Environmental Management* 19(1): 1-15.

Kondolf, G.M. 1995. Five elements for effective evaluation of stream restoration. *Restoration Ecology* 3(2): 133-136.

Landin, M.C. 1995. The role of technology and engineering in wetland restoration and creation. In *Proceedings of the National Wetland Engineering Workshop*, August 1993, ed. J.C. Fischenich et al. Technical Report WRP-RE-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Landres, P.B., J. Verner, and J.W. Thomas. 1988. Ecological uses of vertebrate indicator species: a critique. *Conservation Biology* 2: 316-328.

Leclerc, M., A. Boudreault, J.A. Bechara, and G. Corfa. 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the Instream Flow Incremental Methodology. *Transactions of the America Fisheries Society*. 124: 645-662.

Leopold, L.B., H.L. Silvey, and D.L. Rosgen. 1997. *The Reference Reach Field Book*. Wildland Hydrology, Pagosa Springs, Colorado.

Leopold, L.B., 1994. *A View of the River*. Harvard University Press, Cambridge, Massachusetts.

Li, H. W., C. B. Schreck, R. A. Tubb, K. Rodnick, M. Ahlgren, and A. Crook. 1983. *The Impact of Small-Scale Dams on Fishes of the Willamette River, Oregon and an Evaluation of Fish Habitat Models*. Water Resources Research Institute, Oregon State University, Corvallis, OR. WRRI-91.

Liebrand, C.I., and K.V. Sykora. 1992. Restoration of the vegetation of river embankments after reconstruction. *Aspects of Applied Biology* 29: 249-256.

Livingstone, A.C., and C.F. Rabeni. 1991. Food-habit relations that determine the success of young-of-year smallmouth bass in Ozark streams. In *Proceedings of the First International Symposium on Smallmouth Bass*, ed. D.C. Jackson. Mississippi Agriculture and Forest Experiment Station, Mississippi State University.

Lodge, D.M. 1991. Herbivory on freshwater macrophytes. *Aquatic Botany* 41: 195-224.

Loeb, S.L., and A. Spacie. 1994. *Biological Monitoring of Aquatic Systems*. Papers presented at a symposium held Nov. 29- Dec. 1, 1990, at Purdue University. Lewis Publishers, Boca Raton, Florida.

Lumb, A.M., J.L. Kittle, Jr., and K.M. Flynn. 1990. *Users Manual for ANNIE, a Computer Program for Interactive Hydrologic Analyses and Data Management*. U.S. Geological Survey Water-Resources Investigations Report 89-4080. U.S. Geological Survey, Reston, Virginia.

Luttenegger, J.A., and B.R. Hallberg. 1981. *Borehole Shear Test in Geotechnical Investigations*. American Society of Testing Materials Special Publication No. 740.

Lyons, J., L. Wang, and T.D. Simonson. 1996. Development and validation of an index of biotic integrity for coldwater streams in Wisconsin. *North American Journal of Fisheries Management* 16: 241-56.

MacDonald, L.H., A.W. Smart, and R.C. Wissmar. 1991. *Monitoring Guidelines to Evaluate the Effect of Forestry Activities in Streams in the Pacific Northwest*. EPA/910/9-91-001. USEPA Region 10, Seattle, Washington.

Macrae, C. 1996. Experience from morphological research on Canadian streams: Is control of the two-year frequency runoff event the best basis for stream channel protection? In Effects of Foundation Conference Proceedings, Snowbird, Utah, August 4-9, 1996, pp. 144-160.

Magurran, A.E. 1988. *Ecological Diversity and its Measurement*. Princeton University Press, Princeton, New Jersey.

Malanson, G.P. 1993. Riparian landscapes. Cambridge University Press, Cambridge.

Manley, P.A., et al. 1995. Sustaining ecosystems: a conceptual framework. USDA Forest Service, Pacific Southwest Region, San Francisco, California.

Mann, C.C., and M.L. Plummer. 1995. Are wildlife corridors the right path? *Science* 270: 1428-1430.

Maser, C., and J.R. Sedell. 1994. From the forest to the sea: the ecology of wood in streams, rivers, estuaries, and oceans. St. Lucie Press, Delray Beach, Florida.

May, C., R. Horner, J. Karr, B. Mar, and E. Welch. 1997. Effects of urbanization on small streams in the Puget Sound ecoregion. *Watershed Protection Technique* 2(4): 483-494.

McAnally, W.H., and W.A. Thomas. 1985. User's manual for the generalized computer program system, open-channel flow and sedimentation, TABS-2, main text. U.S. Army Corps of Engineers, Waterways Experiment Station, Hydraulics Lab, Vicksburg, Mississippi.

McClendon, D.D., and C.F. Rabeni. 1987. Physical and biological variables useful for predicting population characteristics of smallmouth bass and rock bass in an Ozark stream. *North Am. J. Fish. Manag*. 7: 46-56.

McGinnies, W.J. 1984. Seeding and planting. In Vegetative rehabilitation and equipment workshop, 38th Annual Report, pp. 23-25. U.S. Forest Service, Rapid City, South Dakota.

Medin, D.E., and W.P. Clary. 1990. Bird populations in and adjacent to a beaver pond ecosystem and adjacent riparian habitat in Idaho. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Meffe, G.K., C.R. Carroll, and contributors. 1994. Principles of conservation biology. Sinauer Associates, Inc., Sunderland, Massachusetts.

Metropolitan Washington Council of Governments (MWCOG). 1997. An existing source assessment of pollutants to the Anacostis watershed, ed. A. Warner, D. Shepp, K. Corish, and J. Galli. Washington, DC.

Milhous, R.T., M.A. Updike, and D.M. Schneider. 1989. Physical Habitat Simulation System Reference Manual—Version II. Instream Flow Information Paper No. 26. U.S. Fish and Wildlife Service Biological Report 89(16). U.S. Fish and Wildlife Service.

Milhous, R.T., J.M. Bartholow, M.A. Updike, and A.R. Moos. 1990. Reference manual for generation and analysis of habitat time series—Version II. U.S. Fish and Wildlife Service Biological Report 90(16). U.S. Fish and Wildlife Service.

Mills, W.B., D.B. Porcella, M.J. Ungs, S.B. Gherini, K.V. Summers, L. Mok, G.L. Rupp, G.L. Bowie and D.A. Haith. 1985. Water quality assessment: a screening procedure for toxic and conventional pollutants in surface and ground water. EPA/600/6-85/002a-b. U.S. Environmental Protection Agency, Office of Research and Development, Athens, Georgia.

Minckley, W.L., and M.E. Douglas. 1991. Discovery and extinction of western fishes: a blink of the eye in geologic time. In Battle against extinction: native fish management in the American West, ed. W.L. Minckley and J.E. Deacon, pp. 7-18. University of Arizona Press, Tucson.

Molinas, A., and C.T. Yang. 1986. Computer program user's manual for GSTARS (Generalized Stream Tube model for Alluvial River Simulation). U.S. Bureau of Reclamation Engineering and Research Center, Denver, Colorado.

Montana Department of Environmental Quality (MDEQ). 1996. Montana Streams Management Guide. ed. C. Duckworth and C. Massman.

Montgomery, D.R., and J.M.Buffington, 1993. Channel classification, prediction of channel response and assessment of channel condition. Report TFW-SH10-93-002. Department of Geological Sciences and Quaternary Research Center, University of Washington, Seattle.

Moore, J.S., D.M. Temple, and H.A.D. Kirsten. 1994. Headcut advance threshold in earth spillways. Bulletin of the Association of Engineering Geologists 31(2): 277-280.

Morin, A., and D. Nadon. 1991. Size distribution of epilithic lotic invertebrates and implications for community metabolism. *Journal of the North American Benthological Society* 10: 300-308.

Moss, B. 1988. Ecology of fresh waters: man and medium. Blackwell Scientific Publication, Boston.

Myers, W.R., and J.F. Lyness. 1994. Hydraulic study of a two-stage river channel. *Regulated Rivers: Research and Management* 9(4): 225-236.

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Connor, P.L. Olson, and E.A. Steel. 1994. Fundamental elements of ecologically healthy watersheds in the Pacific northwest coastal ecoregion. In Watershed management, ed. R. Naiman, pp. 127-188. Springer-Verlag, New York.

National Research Council (NRC). 1983. *An Evaluation of Flood-Level Prediction Using Alluvial River Models*. National Academy Press, Washington, DC.

National Research Council (NRC). 1992. *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy*. National Academy Press, Washington, DC.

National Academy of Sciences. 1995. *Wetlands: Characteristics and Boundaries*. National Academy Press, Washington, DC.

National Park Service (NPS). 1995. Final Environmental Impact Statement, Elwha River Ecosystem Restoration. U.S. Department of the Interior, National Park Service, Olympic National Park, Port Angeles, Washington.

National Park Service (NPS). 1996. Final Environmental Impact Statement, Elwha River Ecosystem Restoration Implementation. U.S. Department of the Interior, National Park Service, Olympic National Park, Port Angeles, Washington.

Nehlsen, W., J.E. Williams, & J.A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries (Bethesda) 16(2): 4-21.

Nehring, R.B., and R.M. Anderson. 1993. Determination of population-limiting critical salmonid habitats in Colorado streams using the Physical Habitat Simulation System. Rivers 4(1): 1-19.

Neill, W.M. 1990. Control of tamarisk by cut-stump herbicide treatments. In Tamarisk control in southwestern United States, pp. 91-98. Cooperative National Park Research Studies Unit, Special Report Number 9. School of Renewable Natural Resources, University of Arizona, Tucson.

Neilson, F.M., T.N. Waller, and K.M. Kennedy. 1991. Annotated bibliography on grade control structures. Miscellaneous Paper HL-91-4. U.S. Army Corps of Engineers, Waterways Experiment Station, CE, Vicksburg, Mississippi.

Nelson, J.M, and J.D. Smith. 1989. Evolution and stability of erodible channel beds. In River Meandering, ed. S. Ikeda and G. Parker. Water Resources Monograph 12, American Geophysical Union, Washington, DC.

Nestler, J., T. Schneider, and D. Latka. 1993. RCHARC: A new method for physical habitat analysis. Engineering Hydrology :294-99.

Nestler, J.M., R.T. Milhouse, and J.B. Layzer. 1989. Instream habitat modeling techniques. Chapter 12 in Alternatives in regulated river management, ed. J.A. Gore and G.E. Petts, Chapter 12. CRC Press, Inc., Boca Raton, Florida.

Newbury, R.W., and M.N. Gaboury. 1993. Stream analysis and fish habitat design: a field manual. Newbury Hydraulics Ltd., Gibsons, British Columbia.

Noss, R.F. 1994. Hierarchical indicators for monitoring changes in biodiversity. In Principles of conservation biology, G.K. Meffe, C.R. Carroll, et al., pp. 79-80. Sinauer Associates, Inc., Sunderland, Massachusetts.

Noss, R.F., and L.D. Harris. 1986. Nodes, networks, and MUMs: preserving diversity at all scales. Environmental Management 10(3): 299-309.

Novotny and Olem. 1994. Water quality, prevention, identification, and management of diffuse pollution. Van Nostrand Reinhold, New York.

NRC. 1990. National Research Council, Committee on Coastal Zone Erosion Management. Managing Coastal Erosion. National Academy Press, Washington, DC.

NRC. 1991. National Research Council. Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy. National Academy Press, Washington, DC.

Nunnally, N.R., and F.D. Shields. 1985. Incorporation of environmental features in flood control channel projects. Technical Report E-85-3. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Odgaard, J. 1989. River-meander model I: development. Journal of Hydraulic Engineering 115(11): 1433-1450.

Odgaard, J. 1987. Streambank erosion along two rivers in Iowa. Water Resources Research 23(7): 1225-1236.

Ohio EPA. 1990. Use of biocriteria in the Ohio EPA surface water monitoring and assessment program. Ohio Environmental Protection Agency, Division of Water Quality Planning and Assessment, Columbus, Ohio.

Olson, R., and W.A. Hubert. 1994. Beaver: Water resources and riparian habitat manager. University of Wyoming, Laramie.

Omernik, J.M. 1987. Ecoregions of the coterminous United States. Ann. Assoc. Am. Geol. 77(1): 118- 125.

Orsborn, J.F., Jr., R.T. Cullen, B.A. Heiner, C.M. Garric, and M. Rashid. 1992. A handbook for the planning and analysis of fisheries habitat modification projects. Department of Civil and Environmental Engineering, Washington State University, Pullman.

Orth, D.J., and R.J. White. 1993. Stream habitat management. Chapter 9 in Inland fisheries management in North America, ed. C.C. Kohler and W.A. Hubert. American Fisheries Society, Bethesda, Maryland.

Osman, A.M., and C.R. Thorne. 1988. Riverbank stability analysis; I: Theory. Journal of Hydraulic Engineering, ASCE 114(2): 134-150.

Pacific Rivers Council. 1996. A guide to the restoration of watersheds and native fish in the pacific northwest, Workbook II, Healing the Watershed series.

Parker, G. 1990. Surface bedload transport relation for gravel rivers. Journal of Hydraulic Research 28(4): 417-436.

Parsons, S., and S. Hudson. 1985. Channel cross-section surveys and data analysis. TR-4341-1. U.S. Department of the Interior, Bureau of Land Management Service Center, Denver, Colorado.

Payne, N.F., and F.C. Bryant. 1994. Techniques for wildlife habitat management of Uplands, New York. McGraw-Hill.

Pearlstine, L., H. McKellar, and W. Kitchens. 1985. Modelling the impacts of a river diversion on bottomland forest communities in the Santee River floodplain, South Carolina. Ecological Modeling 7: 283-302.

Petersen, M.S. 1986. River engineering. Prentice-Hall, Englewood Cliffs, New Jersey.

Petts, G.E. 1984. *Impounded Rivers: Perspective for Ecological Management*. John Wiley and Sons, Inc., New York, NY.

Pielou, E.C. 1993. Measuring biodiversity: quantitative measures of quality. In Our living legacy: Proceedings of a symposium on biological diversity, ed. M.A. Fenger, E.H. Miller, J.A. Johnson, and E.J.R. Williams, pp. 85-95. Royal British Columbia Museum, Victoria, British Columbia.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers. EPA444/4-89-001. U.S. Environmental Protection Agency, Washington, DC.

Platts, W.S., and Rinne. 1985. Riparian and stream enhancement management and research in the Rocky Mountains. North American Journal of Fishery Management 5: 115-125.

Platts, W.S. 1987. Methods for evaluating riparian habitats with applications to management. General Technical Report INT-21. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah.

Poff, N., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. *The Natural Flow Regime: A Paradigm for River Conservation and Restoration*. Bioscience.

Ponce, V.M. 1989. *Engineering Hydrology: Principles and Practices*. Prentice-Hall, Englewood Cliffs, New Jersey.

Rabeni, C.F., and RB. Jacobson. 1993. The importance of fluvial hydraulics for fish-habitat restoration in low-gradient alluvial streams. *Freshwater Biology* 29: 211-220.

Rantz, S.E. 1982. *Measurement and Computation of Streamflow*. Water Supply Paper 2175, 2 vols. U.S. Geological Survey, Washington, DC.

Reiser, D.W., M.P. Ramey, and T.A. Wesche. 1989. Flushing flows. In *Alternatives in Regulated River Management*, ed. M.A. Fenger, E.H. Miller, J.A. Johnson, and E.J.R. Williams, pp. 91-135. CRC Press, Boca Raton, Florida.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reise, A.L. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The role of disturbance in stream ecology. *Journal of the North American Benthological Society* 7: 433-455.

Ricklefs, R.E. 1990. *Ecology*. W.H. Freeman, New York.

Riley, A.L. 1998. *Restoring Stream in Cities: A Guide for Planners, Policy-makers, and Citizens*. Ireland Press.

Rood, S.B., and J.M. Mahoney. 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management* 14: 451-464.

Rosenbaum, W.A. 2005. *Environmental Politics and Policy*. 6th ed. CQ Press, Washington, DC.

Rosgen, D.L. 1996. *Applied River Morphology*. Wildland Hydrology, Colorado.

Salo, E.O., and T.W. Cundy. 1987. *Streamside Management: Forestry and Fishery Interactions*. Contribution No. 57. University of Washington Institute of Forest Resources, Seattle.

Schroeder, R.L., and A.W. Allen. 1992. *Assessment of Habitat of Wildlife Communities on the Snake River, Jackson, Wyoming*. U.S. Department of the Interior, Fish and Wildlife Service.

Schueler, T. 1995. The importance of imperviousness. *Watershed Protection Techniques* 1(3): 100-111.

Schueler, T. 1996. Controlling cumulative impacts with sub-watershed plans. In *Assessing the Cumulative Impacts of Watershed Development on Aquatic Ecosystems and Water Quality, Proceedings of 1996 Symposium*.

Schueler, T. 1987. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, DC.

Sedell J.S., G.H. Reeves, F.R. Hauer, J.A. Stanford, and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. *Environmental Management* 14: 711-724.

Seehorn, M.E. 1985. *Fish Habitat Improvement Handbook*. Technical Publication R8-TP 7. U.S. Department of Agriculture Forest Service, Southern Region.

Shampine, W.J., L.M. Pope, and M.T. Koterba. 1992. *Integrating Quality Assurance in Project Work Plans of the United States Geological Survey*. United States Geological Survey Open-File Report 92- 162.

Shaver, E., J. Maxted, G. Curtis and D. Carter. 1995. Watershed protection using an integrated approach. In *Proceedings from Stormwater NPDES-related Monitoring Needs*, ed. B. Urbonas and L. Roesner, pp. 168-178. Engineering Foundation Conference, Crested Butte, Colorado, August 7-12, 1994.

Shear, T.H., T.J. Lent, and S. Fraver. 1996. Comparison of restored and mature bottomland hardwood forests of Southwestern Kentucky. *Restoration Ecology* 4(2): 111-123.

Shelton, L.R., and P.D. Capel. 1994. *Field Guide for Collecting and Processing Samples of Stream Bed Sediment for the Analysis of Trace Elements and Organic Contaminants for the National Water Quality Assessment Program.* U.S. Geological Survey Open-File Report 94-458.

Shelton, L.R. 1994. *Field Guide for Collecting and Processing Stream-Water Samples for the National Water Quality Assessment Program*. U.S. Geological Survey Open-File Report 94-455.

Shields, F.D., Jr. 1983. Design of habitat structures for open channels. *Journal of Water Resources Planning and Management* 109(4): 331-344.

Shields, F.D., Jr. 1991. Woody vegetation and riprap stability along the Sacramento River Mile 84.5-119. *Water Resources Bulletin* 27: 527-536.

Shields, F.D., Jr., and N.M. Aziz. 1992. Knowledge-based system for environmental design of stream modifications. *Applied Engineering Agriculture* 8(4): 553-562.

Shields, F.D., Jr., S.S. Knight, and C.M. Cooper. 1994. Effects of channel incision on base flow stream habitats and fishes. *Environmental Management* 18: 43-57.

Simon, A. 1992. Energy, time, and channel evolution in catastrophically disturbed fluvial systems. In *Geomophic Systems: Geomorphology,* ed. J.D. Phillips and W.H. Renwick, vol. 5, pp. 345-372.

Simon, A. 1994. Gradation processes and channel evolution in modified west Tennessee streams: process, response, form. U.S. Government Printing Office, Denver, Colorado. *U.S. Geological Survey Professional Paper* 1470.

Simon, A., and C.R. Hupp. 1992. *Geomorphic and Vegetative Recovery Processes Along Modified Stream Channels of West Tennessee*. U.S. Geological Survey Open-File Report 91-502.

Simon, A., and P.W. Downs. 1995. An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology* 12: 215-32.

Smith, B.S., and D. Prichard. 1992. *Management Techniques in Riparian Areas*. BLM Technical Reference 1737-6. U.S. Department of the Interior, Bureau of Land Management.

Smith, D.S., and P.C. Hellmund. 1993. *Ecology of Greenways: Design and Function of Linear Conservation Areas*. University of Minnesota Press, Minnesota.

Smith, C., T. Youdan, and C. Redmond. 1995. Practical aspects of restoration of channel diversity in physically degraded streams. In: *The Ecological Basis for River Management*. D.M. Harper and A.J.D. Ferguson (eds). Chichester, John Wiley & Sons: 269-273.

Sparks, R. 1995. Need for ecosystem management of large rivers and their flooodplains. *BioScience* 45(3): 170.

Spence, B.C., G.A. Lomnscky, R.M. Hughes, and R.P. Novitski. 1996. *An Ecosystem Approach to Salmonid Conservation*. TR-4501-96-6057. ManTech Environmental Research Services Corp., Corvallis, Oregon. (Available from the National Marine Fisheries Service, Portland, Oregon.)

Stalnaker, C.B., K.D. Bovee, and T.J. Waddle. 1996. Importance of the temporal aspects of habitat hydraulics to fish population studies. *Regulated Rivers: Research and Management* 12: 145-153.

Stanley, E.H., S.G. Fisher, and N.B. Grimm. 1997. Ecosytem expansion and contraction in streams. *Bioscience* 47(7): 427-435.

Stoner, R., and T. McFall. 1991. *Woods Roads: A Guide to Planning and Constructing a Forest Roads System*. U.S. Department of Agriculture, Soil Conservation Service, South National Technical Center, Fort Worth, Texas.

Summerfield, M., 1991. *Global Geomorphology*. Longman, Harlow.

Svejcar, T.J., G.M. Riegel, S.D. Conroy, and J.D. Trent. 1992. Establishment and growth potential of riparian shrubs in the northern Sierra Nevada. In *Symposium on Ecology and Management of Riparian Shrub Communities*. USDA Forest Service General Technical Report INT-289. U.S. Department of Agriculture, Forest Service.

Swanson, S. 1989. Using stream classification to prioritize riparian rehabilitation after extreme events. In *Proceedings of the California Riparian Systems Conference*, pp. 96-101. U.S. Department of Agriculture, Forest Service General Technical Report PSW-110.

Sweeney, B.W. 1992. Streamside forests and the physical, chemical, and trophic characteristics of piedmont streams in eastern North America. *Water Science Technology* 26: 1-12.

Telis, P.A. 1991. Low-flow and flow-duration characteristics of Mississippi streams. *U.S. Geological Survey Water-Resources Investigations Report* 90-4087.

Temple, D.M., and J.S. Moore. 1997. Headcut advance prediction for earth spillways. *Transactions ASAE* 40(3): 557-562.

Terrell, J.W. and J. Carpenter. 1998. *Selected Habitat Suitability Index Model Evaluations*. National Biological Service Fort Collins, Colorado, Mid-continent Ecological Science Center.

Thomann, R.V., and J.A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. Harper & Row, New York.

Thomas and Bovee. 1993. Application and testing of a procedure to evaluate transferability of habitat suitability criteria. *Regulated Rivers Research and Management* 8(3): 285-294, August 1993.

Thorne, C.R., R.G. Allen, and A. Simon. 1996. Geomorphological river channel reconnaissance for river analysis, engineering and management. *Transactions of the Institute for British Geography* 21: 469-483.

Thorne, C.R., S.R. Abt, F.B.J. Barends, S.T. Maynord, and K.W. Pilarczyk. 1995. *River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone*. John Wiley and Sons, Ltd., Chichester, UK.

Thorne, C.R., H.H. Chang, and R.D. Hey. 1988. Prediction of hydraulic geometry of gravel-bed streams using the minimum stream power concept. In *Proceedings of the International Conference on River Regime*, ed. W.R. White. John Wiley and Sons, New York.

Thorne, C.R., and A.M. Osman. 1988. River bank stability analysis II: applications. *Journal of Hydraulic Engineering* 114(2): 151-172.

Thorne, C.R., and L.W. Zevenbergen. 1985. Estimating mean velocity in mountain rivers. *Journal of Hydraulic Engineering* 111(4): 612-624.

Thornton, K.W., B.L. Kimmel, and F.E. Payne, eds. 1990. *Reservoir Limnology: Ecological Perspectives*. John Wiley and Sons, Inc., New York, NY.

Trimble, S. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 278: 1442-1444.

U.S. Army Corps of Engineers. No date. *The WES Handbook on Water Quality Enhancement Techniques for Reservoirs and Tailwaters*. U.S. Army Corps of Engineer Research and Development Center Waterways Experiment Station, Vicksburg, MS.

USACE. 1989. *Sedimentation Investigations of Rivers and Reservoirs*. Engineer Manual No. 1110-2-4000. Department of the Army, United States Army Corps of Engineers, Washington, DC.

USACE. 1990. *Vicksburg District Systems Approach to Watershed Analysis for Demonstration Erosion Control Project, Appendix A.* Demonstration Erosion Control Project Design Memorandum No. 54. Vicksburg District, Vicksburg, Mississippi.

USACE. 1991. *Hydraulic Design of Flood Control Channels*. USACE Headquarters, EM1110-2-1601, Washington, DC.

USACE. 1993. *Demonstration Erosion Control Project Coldwater River Watershed*. Supplement I to General Design Memorandum No. 54. Vicksburg District, Vicksburg, Mississippi.

USDA-NRCS. 1998. *Stream Visual Assessment Protocol*. United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Data Center, Portland, Oregon. ftp://ftp.wcc.nrcs.usda.gov/downloads/wqam/svapfnl.pdf.

USDOI-BOR. 1997. *Water Measurement Manual*. A Water Resources Technical Publication. United States Department of the Interior, Bureau of Reclamation. U.S. Government Printing Office, Washington, DC.

USEPA. 2002. *National Water Quality Inventory 2000 Report*. EPA-841-R-02-001, U.S. Environmental Protection Agency, Office of Water, Washington, DC. http://www.epa.gov/305b/2000report.

USEPA. 1997. *Top Ten Watershed Lessons Learned*. EPA 840-F-97-001, U.S. Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/lessons.

USEPA. 1995. *Ecological Restoration: a Tool to Manage Stream Quality*. EPA 841-F-95-007, U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC. http://www.epa.gov/owow/nps/Ecology.

USEPA. 1995. Volunteer Stream Monitoring: a Method Manual. EPA 841-D-95-001, U.S. Environmental Protection Agency, Washington, DC.

USEPA. 1993. *Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Costal Waters*. EPA 840-B-92-002, U.S. Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/nps/MMGI.

USEPA. 1992. *Storm Water Sampling Guidance Document*. EPA 833-B-92-001, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/npdes/pubs/owm0093.pdf.

USEPA. 1991. *Baywide Nutrient Reduction Strategy 1990 Progress Report*. U.S. Environmental Protection Agency Chesapeake Bay Program, Annapolis, MD.

USEPA. 1990. *National Guidance: Water Quality Standards for Wetlands*. EPA 440-S-90-011, U.S. Environmental Protection Agency, Office of Water, Washington, DC. http://www.epa.gov/OWOW/wetlands/regs/quality.html.

USEPA. 1989. *Sediment Classification Methods Compendium*. EPA 823-R-92-006, U.S. Environmental Protection Agency, Office of Water, Washington, DC. http://www.epa.gov/waterscience/library/sediment/classmethods.pdf.

USEPA. 1986. *Ambient Water Quality Criteria for Dissolved Oxygen*. EPA 440/5-86-003, U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC.

USEPA. 1986. *Quality Criteria for Water 1986*. EPA 440/5/86-001, U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC. http://www.epa.gov/waterscience/criteria/goldbook.pdf.

USFS. 1965. *Range Seeding Equipment Handbook*. U.S. Forest Service, Washington, DC.

USFWS. 1981. *Standards for the Development of Habitat Suitability Index Models (ESM 103)*. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC.

USFWS. 1997. *A System for Mapping Riparian Areas in the Western United States*. United States Fish and Wildlife Service National Wetlands Inventory. Washington, DC. December.

USFWS. 1980. *Habitat Evaluation Procedures (HEP) (ESM 102)*. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC. http://policy.fws.gov/ESMindex.html.

Van Winkle, W., H.I. Jager, and B.D. Holcomb. 1996. *An Individual-based Instream Flow Model for Coexisting Populations of Brown and Rainbow Trout*. Electric Power Research Institute Interim Report TR-106258. Electric Power Research Institute.

Van Haveren, B.P. 1986. Management of instream flows through runoff detention and retention. *Water Resources Bulletin WARBAQ* 22(3): 399-404.

Vogel, R.M. and C.N. Kroll. 1989. Low-flow frequency analysis using probability-plot correlation coefficients. *Journal of Water Resources Planning and Management, ASCE* 115 (3): 338-357.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. *Design of Water Quality Monitoring Systems*. Van Nostrand Reinhold, New York.

Ward, J.V. 1985. Thermal characteristics of running waters. *Hydrobiologia* 125: 31-46.

Welsch, D.J. 1991. *Riparian Forest Buffers: Function and Design for Protection and Enhancement of Water Resources*. USDA Forest Service, Northeastern Area State and Private Forestry Publication No. NA-PR-07-91. U.S. Department of Agriculture Forest Service, Radnor, Pennsylvania.

Wesche, T.A. 1985. Stream channel modifications and reclamation structures to enhance fish habitat. Chapter 5 in *The Restoration of Rivers and Streams*, ed. J.A. Gore. Butterworth, Boston.

Wharton, G. 1995. The channel-geometry methods: guidelines and applications. *Earth Surface Processes and Landforms* 20(7): 649-660.

Wildman, L., P. Parasiewicz, C. Katopodis, and U. Dumont. No date. *An Illustrative Handbook on Nature-Like Fishways - Summarized Version*. http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=1806.

Williams, G.P. and M.G. Wolman. 1984. Downstream effects of dams on alluvial rivers. *U.S. Geological Survey Professional Paper* 1286, 83 pp.

Williams, G.W. 1986. River meanders and channel size. *Journal of Hydrology* 88: 147-164.

Williamson, S.C., J.M. Bartholow, and C.B Stalnaker. 1993. Conceptual model for quantifying pre-smolt production from flow-dependent physical habitat and water temperature. *Regulated Rivers: Research and Management* 8: 15-28.

Yang, C.T., M.A. Trevino, and F. J.M. Simoes. 1998. *Users Manual for GSTARS 2.0 (Generalized Stream Tube Model for Alluvial River Simulation Version 2.0)*. U.S. Bureau, Technical Service Center, Denver, Colorado.

Yang, C.T. 1996. *Sediment Transport Theory and Practice*. The McGraw-Hill Companies, Inc. New York.

Yoakum, J., W.P. Dasmann, H.R. Sanderson, C.M. Nixon, and H.S. Crawford. 1980. Habitat improvement techniques. In Wildlife *Management Techniques Manual*, 4th ed., rev., ed. S.D. Schemnitz, pp. 329- 403. The Wildlife Society, Washington, DC.

Journals

Biological Conservation
http://www.elsevier.com/wps/find/journaldescription.cws_home/405853/description#description

Conservation Biology
http://conbio.net/SCB/Publications/ConsBio

Ecological Engineering
http://www.elsevier.com/wps/find/journaldescription.cws_home/522751/description#description

Environment
http://www.heldref.org/env.php

Environmental Management
http://springerlink.metapress.com/app/home/journal.asp?wasp=m3gkvgwyth25m4vxjywv&referrer=parent&backto=linkingpublicationresults,1:100370,1

Environmental Science & Engineering
http://www.esemag.com

Fisheries
http://www.fisheries.org/html/index.shtml

Freshwater Biology
http://www.blackwellpublishing.com/journal.asp?ref=0046-5070&site=1

International Journal on Hydropower and Dams
http://www.hydropower-dams.com

Journal of the American Water Resources Association (Water Resources Bulletin prior to 1997)
http://www.awra.org/jawra

Journal of Coastal Conservation
http://www.opuluspress.se/journals_about.asp?id=10

Journal of Coastal Research
http://www.cerf-jcr.org

Journal of Environmental Hydrology
http://www.hydroweb.com/journal-hydrology.html

Journal of Environmental Engineering
http://www.pubs.asce.org/journals/ee.html

Journal of Environmental Management
http://www.elsevier.com/wps/find/journaldescription.cws_home/622871/description#description

Journal of the North American Benthological Society
http://www.benthos.org/JNABS

Journal of Soil and Water Conservation
http://www.swcs.org/t_pubs_journal.htm

Land and Water: The Magazine of Natural Resource Management and Restoration
http://www.landandwater.com

Nonpoint Source News Notes – Terrene Institute
http://www.epa.gov/owow/info/NewsNotes

North American Journal of Fisheries Management
http://afs.allenpress.com/afsonline/?request=index-html

Ocean & Coastal Management
http://www.elsevier.com/wps/find/journaldescription.cws_home/405889/description#description

Regulated Rivers: Research and Management
http://www3.interscience.wiley.com/cgi-bin/jhome/4393

Shore & Beach
http://www.asbpa.org/shore_beach.html

Water Environment & Technology
http://www.wef.org/Periodicals/WaterEnvTech

Listservers

NPSINFO Listserver – EPA
http://www.epa.gov/owow/nps/changes.html

RiverCurrents Online – American Rivers
http://www.americanrivers.org/index.php?module=HyperContent&func=display&cid=798

WaterNews Listserver – EPA
http://www.epa.gov/water/waternews/

Educational Materials

American Rivers: Dam Removal Case Studies
http://www.amrivers.org/index.php?module=HyperContent&func=display&cid=113

American Rivers: Dam Removal Tool Kit
http://www.amrivers.org/drtk.html

Educational Resources – EPA
http://www.epa.gov/epahome/educational.htm

Greenwings – Ducks Unlimited
http://www.greenwing.org/greenwings/home2.htm

National Wildlife Federation Kids Page
http://www.nwf.org/kids

Project WET (Water Education for Teachers)
http://www.projectwet.org

USGS Water Resources Outreach Program
http://water.usgs.gov/outreach/OutReach.html

Additional Information

EPA. 1994. *A State and Local Government Guide to Environmental Program Funding Alternatives*. EPA 841-K-94-001. http://www.epa.gov/owow/nps/MMGI/funding.html

EPA. 1994. *A Tribal Guide to the Section 319(h) Nonpoint Source Grant Program*. EPA 841-S-94-003.

EPA. 1997. *Catalog of Federal Funding Sources for Watershed Protection*. EPA 841-B-97-008. http://www.epa.gov/owowwtr1/watershed/wacademy/fund.html

EPA. 1994. *Section 319 Success Stories: Volume I*. EPA 841-S-94-004.
http://www.epa.gov/owow/nps/Success319

EPA. 1997. *Section 319 Success Stories: Volume II – Highlights of State and Tribal Nonpoint Source Programs*. EPA 841-R-97-001.
http://www.epa.gov/owow/nps/Section319II

EPA. 2002. *Section 319 Success Stories: Volume III*.
http://www.epa.gov/owow/nps/Section319III

EPA Clean Lakes Program
http://www.epa.gov/owow/lakes/cllkspgm.html

EPA Environmental Finance Information Network (EFIN)
http://www.epa.gov/efinpage/efin.htm

EPA Nonpoint Source Pollution Control Program Homepage
http://www.epa.gov/OWOW/NPS

EPA Surf Your Watershed
http://www.epa.gov/surf

EPA Watershed Academy
http://www.epa.gov/owow/watershed/wacademy

International Commission on Large Dams
http://www.icold-cigb.org/Dresdenpress%20.htm

International Rivers Network
http://www.irn.org

U.S. Department of Agriculture, Farm Service Agency
http://www.fsa.usda.gov/pas

U.S. Department of Agriculture, Natural Resources Conservation Service
http://www.nrcs.usda.gov

U.S. Department of the Interior, Bureau of Reclamation
http://www.usbr.gov

U.S. Department of the Interior, National Park Service
http://www.nps.gov

U.S. Department of the Interior, U.S. Fish and Wildlife Service
http://www.fws.gov

U.S. Department of the Interior, U.S. Geological Survey
http://www.usgs.gov

Watershedss, (Water, Soil, and HydroEnvironmental Decision Support System) – North Carolina State University
http://www.water.ncsu.edu/watershedss

Waterways Experiment Station – U.S. Army Corps of Engineers
http://www.wes.army.mil

World Commission on Dams
http://www.dams.org

Appendix A
Federal, State, Nonprofit, and Private Financial and Technical Assistance Programs

This appendix contains examples of financial and technical assistance programs to protect and restore hydrology. It also contains incentive programs offered by state, nonprofit, and private organizations. For each agency and organization, contacts are provided for further information.

Federal Programs

United States Army Corps of Engineers

The United States Army Corps of Engineers (USACE) provides design and engineering services and construction support for a variety of military and civilian projects worldwide. One civil duty includes protecting the integrity of the navigable waters of the United States, wetland resources, and the nation's water resources. USACE's duties also include maintaining navigation and shipping channels, providing emergency response to natural disasters, regulating discharges of dredged or fill material, operating and maintaining flood control reservoirs, and regulating activities in wetlands.

- Wetlands are managed by the USACE by the issuance or denial of Clean Water Act section 404 and other permits authorizing certain activities in wetlands and other waters of the United States. Of the approximately 15,000 permits requested each year, approximately 67 percent are granted.

For more information on the U.S. Army Corps of Engineers, contact:
U.S. Army Corps of Engineers Regulatory Branch
20 Massachusetts Avenue, NW
CECW-OR
Washington, DC 20314-1000
Phone: (202) 761-0199
Web site: www.usace.army.mil

United States Department of Agriculture

The missions of the United States Department of Agriculture (USDA) are to enhance the quality of life for the American people by supporting production of agriculture by

- Ensuring a safe, affordable, nutritious, and accessible food supply.
- Caring for agricultural, forest, and range lands.
- Supporting sound development of rural communities.
- Providing economic opportunities for farm and rural residents.
- Expanding global markets for agricultural and forest products and services.
- Working to reduce hunger in America and throughout the world.

Within the USDA, the Natural Resources Conservation Service, Farm Service Agency, Forest Service, Cooperative State Research, Education, and Extensive Service, and the National Association of Conservation Districts participate in wetland incentives programs.

USDA Farm Service Agency

The ***Farm Service Agency (FSA)*** of the USDA is interested in ensuring the well-being of American agriculture, the environment, and the American public through efficient management of farm commodities, emergency and disaster assistance, domestic and international food assistance and credit programs, and conservation and environmental programs.

- The Conservation Easement Debt Cancellation Program of the FSA allows for reduction of Farmer's Home Administration borrower debt in exchange for granting conservation easements for valuable habitat, including wetlands, on their property for a period of not less than 50 years.
- The Conservation Reserve Enhancement Program (CREP) is a cooperative partnership between the federal and state governments. The program has been administered by the USDA FSA since 1986. The program provides ranchers and farmers with incentives to remove land from production. These lands are then planted with trees or grass to prevent

erosion, improve air and water quality, and establish wildlife habitat.

- Farmers nationwide have contributed 36 million acres of cropland into the Conservation Reserve Program (CRP) (as of 1997). These farmers receive annual rental payments, cost-sharing, and technical assistance to plant vegetation for land they put into reserve for 10 to 15 years. Few of the fields placed in reserve have yet to have their full wetlands values restored. Although CRP funds are no longer available to help restore wetlands on these lands, the landowner may do so at any time with any other non-USDA assistance. The CRP is administered by the CFSA in cooperation with the NRCS.The Conservation Reserve Enhancement Program (CREP), under the Conservation Reserve Program, is a 1996 initiative continued in the 2002 Farm Bill. CREP targets state and federal funds to achieve shared environmental goals of national and state significance. The program uses financial incentives to encourage farmers and ranchers to voluntarily protect soil, water, and wildlife resources.
- Grassland Reserve Program (GRP) - This 2002 provision of the Farm Bill will use 30-year easements and rental agreements to improve management, restore, or conserve up to 2 million acres of private grasslands. 500,000 acres are to be reserved for protected tracts of 40 acres or less as native grasslands. Restoration cost payments may be up to 75 percent of eligible projects.

For more information, contact:

U.S. Department of Agriculture
Farm Service Agency
14th and Independence Avenues, SW
Washington, DC 20250
Phone: (202) 720-3467
Web site: http://www.fsa.usda.gov/

The ***Forest Service*** (FS) is a USDA agency that manages public lands in national forests and grasslands and is also the largest forestry research organization in the world. The agency provides technical and financial assistance to state and private forestry agencies "to provide the greatest amount of good for the greatest amount of people in the long run."

- Forest Stewardship Program (FSP) and Stewardship Incentive Program (SIP) - FSP and SIP are U.S. Forest Service programs established to help landowners protect and enhance their forestlands and associated wetlands. FSP provides technical assistance to help landowners enhance and protect the timber, fish and wildlife habitat, water quality, wetlands, and recreational and aesthetic values of their property. SIP provides cost-share assistance to private landowners for implementing the management plans developed under FSP.

  http://www.fs.fed.us/spf/coop/programs/loa/fsp.shtml
- Forest Legacy Program - The Forest Legacy Program is a U.S. Forest Service program that purchases easements to conserve environmentally important forestlands, which often contain wetlands, threatened with conversion to other uses. Puerto Rico and 17 states are currently active in the program (as of 1997) (USEPA, 1997c).
- Forest Land Enhancement Program (FLEP) - Authorized in the 2002 Farm Bill, the FLEP is a new conservation program to provide financial, technical, and educational assistance to State Foresters who will help private landowners actively manage their land. It replaces and expands the Stewardship Incentive program and Forestry program. The new FLEP will provide up to $100 million over 6 years to private, non-industrial forest

owners. The new title also provides $210 million to help fight fire on private land and address fire prevention.

For more information on the Forest Service, contact:
U.S. Department of Agriculture Forest Service
Public Affairs Office
P.O. Box 96090
Washington, DC 20090-6090
Phone: (202) 205-1760
Fax: (202) 205-1765
Web site: http://www.fs.fed.us

The ***Natural Resources Conservation Service*** (NRCS) [formerly USDA Soil Conservation Service] is a federal agency that works in partnership with the public to conserve and sustain natural resources. The NRCS provides technical assistance to landowners in development of resource management systems that conserve soil, air, water, plant, and animal resources. This agency employs soil scientists, plant scientists, and engineers who can provide assistance in identifying, restoring, enhancing, and creating wetlands. The NRCS provides technical assistance and information for making wetland determinations for wetland protection and management programs; developing conservation plans for protecting and managing wetlands; providing income-producing alternatives for use and management of wetlands; developing standards and specifications and designing and installing conservation measures for wetland restoration, creation, and enhancement; providing information on plant materials for wetland planting; and providing soil surveys and information for identifying, planning, and managing wetlands. Wetland incentive programs administered by the NRCS include the following:

- Conservation of Highly Erodible Lands - The highly erodible land part of the 1985 Food Security Act restricts access by agricultural producers who grow crops on highly erodible land to specified farm program benefits. The goals are to reduce soil lost to wind and water erosion and to improve water quality. Compliance requires the development of a conservation plan for all highly erodible fields on a farm. The plans must be approved by the producer, NRCS, and the local Natural Resources District. NRCS provides technical assistance to the producer in developing the plan.
- Conservation of Private Grazing Land - This program was authorized by the 1996 Farm Bill for the purpose of providing technical and educational assistance to owners of private grazing lands. It offers opportunities for better land management, erosion reduction, water conservation, wildlife habitat, and improving soil structure.
- Environmental Quality Incentives Program (EQIP) - EQIP provides a voluntary conservation program for farmers and ranchers to address threats to soil, water, and related natural resources. It offers 5- to 10-year contracts that provide incentive payments and cost-sharing for conservation practices called for in the site-specific plan. NRCS conducts an evaluation of the environmental benefits the producer offers, and funding is approved for the highest-priority applications first. Cost sharing may pay up to 75 percent of the costs of certain conservation practices, such as grassed waterways, filter strips, and other practices important to improving and maintaining the health of natural resources in the area.
- National Conservation Buffer Initiatives - The National Conservation Buffer Initiative plans to install 2 million miles of conservation buffers nationwide by the year 2000. This initiative does not specifically target streamside areas for buffers, but it includes buffers between fields, wind breaks, and a variety of other practices.
- Resource Conservation and Development (RC&D) - The RC&D is a program for landowner associations and interest groups that allocates grants to RC&D areas to accelerate resource protection projects and programs in multicounty areas as a base for economic development and environmental protection.
- Swampbuster - The Swampbuster program is a provision of the Food Security Act of 1985. It discourages the draining, filling, and other alteration of wetlands for agricultural uses

through financial disincentives. The NRCS determines compliance with Swampbuster provisions and assists farmers in identifying wetlands and developing wetland protection, restoration, and creation plans.

- Wetlands Reserve Program (WRP) - The WRP is a voluntary USDA program offering landowners a chance to receive payments for restoring and protecting wetlands. Authorized by the Food Security Act of 1985, the WRP provides a unique opportunity for farmers to retire marginal lands through permanent easements, 30-year easements, or restoration cost-share agreements and reap the many benefits of having wetlands on their property.
- Wildlife Habitat Incentives Program (WHIP) - WHIP is a voluntary program for people who want to develop and improve wildlife habitat on private lands. The USDA provides both technical assistance and cost-share incentives to help establish and improve fish and wildlife habitat. Participants who own or control land agree to prepare and implement a wildlife habitat development plan.

For more information on the NRCS programs, contact:
U.S. Department of Agriculture
Natural Resources Conservation Service
14th and Independence Avenues, SW
Washington, DC 20250
Phone: (202) 720-4525
Web sites: http://www.nrcs.usda.gov/
http://www.nrcs.usda.gov/programs/farmbill/2002/

United States Department of The Interior

The mission of the United States Department of the Interior (DOI) is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American people.

The **Bureau of Reclamation** (Reclamation) is an agency within the DOI whose mission is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Reclamation operates and manages dams and reservoirs throughout the western United States for irrigation, hydroelectricity, municipal and industrial water supply, fish and wildlife, and recreation uses.

- Reclamation's Wetland Development Program restores, enhances, and develops wetlands, riparian habitat, and associated habitats on Reclamation lands and on lands associated with water supplies and systems affected by Reclamation projects. The program aims to improve water quality and habitat for wildlife at Reclamation projects and to support the North American Waterfowl Management Plan and other migratory bird initiatives. Although not required, almost every project involves partnership development and cost-sharing with federal and non-federal entities. Recent collaborative projects include restoration of the 300-acre Alpine wetland on the Idaho-Wyoming border, restoration of the 8,000-acre Rincon Bayou-Nueces estuary on the Texas Gulf Coast, development of wetlands to improve waste-water and provide habitat for endangered species in Arizona and Nevada, restoration of vernal pools and habitat for endangered species in California, development and restoration of wetlands in the Devils Lake basin in North Dakota to attenuate runoff and reduce high lake levels in Devils Lake, restoring wetlands and water control structures on national wildlife refuges and waterfowl management areas, and working with irrigation districts to develop wetlands to improve the quality of return flows.
- Reclamation partnerships with the National Fish and Wildlife Foundation have funded wetland restoration and development projects

for fish and wildlife throughout the western United States. Funds have been provided to restore wetlands in Oklahoma for migratory birds, develop wetlands for endangered species in Nevada, and stabilize channel morphology and restore riparian habitat to improve water quality in Montana.

- The DOI's National Irrigation Water Quality Program was established in 1986 to develop coordinated remediation plans with appropriate federal, state, and local entities to implement corrective actions where irrigation drainage from federal irrigation projects has affected endangered species or migratory birds or created water quality problems from naturally occurring sources. Reclamation is responsible for program management. The U.S. Geological Survey, Fish and Wildlife Service, and Bureau of Indian Affairs work cooperatively with Reclamation on program oversight and technical issues.

For more information, contact:
Department of the Interior
Bureau of Reclamation, Public Affairs
1849 C Street, NW

Main Interior Building
Washington, DC 20240
Phone: (202) 513-0575
Web Site: http://www.usbr.gov/

National Park Service (NPS) was created to promote and regulate the use of national parks to conserve scenery and the natural and historic resources within them to serve for enjoyment today and in the future.

- The Rivers, Trails, and Conservation Assistance Program (RTCA) is a program that works in partnership with project cooperators to help them obtain funding for their projects. Several projects have some focus on wetland protection and restoration. Examples of such programs include the protection of 2,500 acres of wetlands in the upper Des Plaines River Macrosite (Illinois and Wisconsin) and the rehabilitation of habitat of wetlands in the Missouri River Corridor (Kansas, Nebraska, and Iowa).

For more information on NPS projects, contact:
U.S. Department of the Interior
National Park Service
1849 C Street, NW
Washington, DC 20240
Phone: (202) 208-6843
Web site: http://www.nps.gov/

United States Fish and Wildlife Service (USFWS) is the principal federal agency responsible for conserving, protecting, and enhancing certain fish and wildlife and their habitats, in particular migratory game and endangered species. Among other roles, the USFWS administers the federal Endangered Species Act and establishes and maintains a system of more than 500 National Wildlife Refuges nationwide. The USFWS also manages the taking of migratory waterfowl and conducts research and monitoring programs to inventory and record changes in populations of fish and wildlife and in habitats.

- Challenge Cost Share Program - The USFWS designed this program to manage, restore, and enhance fish and wildlife resources and natural habitats on public and private lands. The program is a partnership with non-federal public and private institutions, organizations, and individuals. Challenge Cost Share allows the USFWS to provide matching funds for projects that support the management, restoration, and protection of natural resources on more than 500 National Wildlife Refuges, 70 fish hatcheries, research facilities, and private lands.

- The National Coastal Wetlands Conservation Grant Program was founded with the enactment of the Coastal Wetlands Planning, Protection, and Restoration Act (Title III of P.L. 101-646) in 1990. The program allows the USFWS to work directly with states to acquire, restore, manage, or enhance coastal wetlands through a matching grants program. Louisiana is the only coastal state that is not eligible for grant monies because that state has its own coastal wetland program under the act. The program has awarded $53 million to 24 states and one territory, allowing more than 63,000 acres of coastal wetlands to be acquired, protected, or restored.
- The Small Wetlands Acquisition Program (SWAP) was created by the Migratory Bird Hunting Stamp Act to preserve wetlands and increase waterfowl production. The primary focus of the program is on the Prairie Pothole Region of the United States (Montana, North Dakota, South Dakota, Iowa, and Minnesota). Prairie potholes are freshwater depressions, usually less than 2 feet deep and smaller than 1 acre, that were carved by glaciers. Since 1989 more than 23,000 easements on 1.2 million acres of wetlands have been obtained by the USFWS to protect these areas.
- Conservation Easement Debt Cancellation Program - The Consolidated Farm Service Agency (CFSA) allows for reduction of Farmer’s Home Administration (FmHA) borrower debt in exchange for granting conservation easements for valuable habitat, including wetlands, on their property for a period of not less than 50 years. Wetlands placed in easements by farmers for FmHA debt reduction may be managed by the USFWS. FmHA has become part of the CFSA; therefore, CFSA now manages FmHA loans.
- The North American Wetlands Conservation Act (NAWCA), established in 1989, encourages partnerships among public agencies and other interests in the United States, Canada, and Mexico to (1) protect, enhance, restore, and manage wetland ecosystems and other habitats for migratory birds, fish, and wildlife in North America; (2) maintain current or improved distribution of migratory bird populations; and (3) sustain an abundance of waterfowl and other migratory birds consistent with the goals of the North American Waterfowl Management Plan and international treaty obligations.
- The North American Waterfowl Management Plan (NAWMP) was signed in 1986 between the United States and Canada to protect, restore, and enhance wetlands important to waterfowl and other wetland-dependent bird species. Mexico has recently signed the NAWMP as well. The NAWMP’s primary objective is to return waterfowl populations to levels observed in the 1970s, when fall flights exceeded 80 million ducks. The plan is implemented at the grassroots level by partnerships called joint ventures. Wetlands identified under NAWMP as "areas of major concern" for waterfowl habitat (e.g., migration, nesting, and forage areas) are targets for these joint ventures.

Examples of NAWMP projects include the Gulf Coast Joint Venture, which focuses on perpetuating healthy wintering grounds for migrating waterfowl and other birds and wildlife species along the Gulf Coast from Alabama to Texas, and the Lower Mississippi Valley Joint Venture, covering 22 million acres in 10 Delta states. Its target is the enhancement of wetlands on private lands. In California, there are three joint ventures: the Central Valley Habitat Joint Venture (1988), the Pacific Coast Joint Venture (1994), and the Intermountain West Joint Venture (1994). A fourth, covering the southern region of the state, is being planned.

Partners for Fish and Wildlife

The **Partners for Fish and Wildlife Program** (PFFW), also known as the Private Lands Assistance and Restoration Program, offers technical and cost-share assistance to landowners who wish to restore wildlife habitat, including degraded or converted wetlands and those upland habitats that meet specific eligibility criteria. The objectives of PFFW programs, which operate in all 50 states, are to restore, enhance, and manage wetlands for fish and wildlife habitat; promote profitable land use for agriculture, industry, and private landowners; and promote a wise and lasting land-use ethic. Formerly known as the Partners for Wildlife Program (PFW), the USFWS will enter into agreements with private landowners for the restoration, creation, and enhancement of wetlands and associated habitats. The PWF and PFFW have protected almost 1 million acres of wetlands and other habitats since 1987.

- The Montana PFFW has focused on five areas for restoration projects: Northern Continental Divide Ecosystem, the Rocky Mountain Front, Beaver Creek Prairie Pothole Joint Venture, and Centennial and Big Hole Valleys. Under these projects, Montana PFFW has worked with the Montana Department of Fish, Wildlife and Parks, Ducks Unlimited, Pheasants Forever, and the Flathead Indian Reservation to restore wetlands, fence riparian areas, and manage livestock.
- In South Dakota, 1,879 landowners are participating in the program (as of 1997).
- The Prairie Wetlands Project (PWP) was designed to accomplish the goals and objectives of the Gulf Coast Joint Venture (GCJV); the PWP is a partnership effort to restore, create, or enhance wetlands beneficial for waterfowl and other wildlife use. PWP projects include management of water on cropped lands, restoration of converted wetlands, enhancement of natural wetlands, or creation of wetlands on non-wetland sites. The PWP is a FWS partnership effort to restore, create, or enhance wetlands beneficial for waterfowl and other wildlife. In exchange for financial and technical incentives, landowners develop a management plan, which may include management of water on cropped lands, restoration of converted wetlands, enhancement of natural wetlands, or creation of wetlands on non-wetland sites. Cost-share assistance of up to 75 percent is available.

For more information on the USFWS programs, contact:
U.S. Department of the Interior
Fish and Wildlife Service, Division of Federal Aid
Arlington Square, Room 140
4401 North Fairfax Drive
Arlington, VA 22203
Phone: (703) 358-2156
Fax: (703) 358-1837
Web site: http://www.fws.gov/

For information specific to the Coastal Habitat Conservation Program, contact USFWS':
Division of Habitat Conservation
4401 N. Fairfax Drive Room 400
Arlington, VA 22203
Phone: (703) 358-2201
Fax: (703) 358-2232
Web site: http://www.fws.gov/coastal/coastalgrants

USGS

The **United States Geological Survey** (USGS) provides the nation with reliable, impartial information to describe and understand the earth.

- The National Wetlands Research Center (NWRC) was established by USGS to develop and disseminate scientific information needed for understanding the ecology and values of the nation's wetlands and for managing and restoring wetland habitats and associated plant and animal communities. The Water Quality Incentives Program (WQIP) is a voluntary incentive program designed to protect water sources on farmlands through 3- to 5-year agreements with the CFSA. These agreements require the development and implementation of a water quality management program that provides water quality benefits, wetland protection, and wildlife benefits. The Wetland Ecology Branch of the NWRC conducts research related to sustainable management and restoration of the nation's coastal saltwater wetlands, coastal

- and inland freshwater wetlands, submerged aquatic ecosystems, and coastal prairie.

For more information, contact:
U.S. Geological Survey
12201 Sunrise Valley Drive
Reston, VA 20192
Phone: (703) 648-4748
Web site: http://www.usgs.gov/

United States Environmental Protection Agency

The mission of the U.S. Environmental Protection Agency (EPA) is to protect human health and to safeguard the natural environment—air, water, and land—upon which life depends.

EPA is responsible for implementing federal laws designed to protect the nation's natural resources. This is done primarily through regulation, but EPA has also developed a wide variety of funding, planning, and education programs. EPA has the authority to regulate wetlands under section 404 of the Clean Water Act.

Under Section 319 of the Clean Water Act, EPA awards funds to states and eligible tribes to implement NPS management programs. These funds can be used for projects that include protection and restoration of wetlands and the development of vegetated treatment systems. More information about the Section 319 program is provided at *www.epa.gov/owow/nps/cwact.html*.

- EPA's Wetland State Partnership Grant Program provides money to states that encourage wetlands protection and restoration. For example, the Division of Natural Heritage of the Tennessee Department of Environment and Conservation received a $208,207 grant to encourage property owners to voluntarily enroll wetlands in state and federal wetland conservation and assistance programs; to work with state, county, and local governments to avoid or minimize impacts on wetlands; and to encourage voluntary wetland conservation in four of the state's counties: Fayette, Franklin, Lauderdale, and Rutherford.
- The 51 Clean Water State Revolving Funds (SRF) programs currently issue approximately $3 billion in loans annually. SRF loans are issued at below market rates (0 percent to less than market), offering borrowers significant savings over the life of the loan. Based on the serious threats to wetland resources across the country, EPA would like to see the SRF become a major source of funding for wetland protection. In creating the SRF, Congress ensured that it would be able to fund virtually any type of water quality project, including nonpoint source, wetlands, estuary, and other types of watershed projects, as well as more traditional municipal wastewater treatment systems. Today, the SRF provisions in the Clean Water Act give no more preference to one category or type of project than any other. Wetland projects typically fall under approved state nonpoint source management plans or are included in national estuary management plans. Constructed wetlands may be considered wastewater or stormwater management projects and are also eligible for funding. SRF-fundable projects include wetland restoration, wetland protection, and constructed wetlands.

For more information, contact your Clean Water State Revolving Fund Program or contact:
The Clean Water State Revolving Fund Branch
U.S. EPA
Ariel Rios Building
1200 Pennsylvania Ave., NW
Washington, DC 20460
Phone: (202) 260-7359
Web site: http://www.epa.gov/OWM

For more information on EPA's other wetlands programs, contact:
U.S. Environmental Protection Agency
OWOW, OW, Office of Wetlands
Phone: (800) 832-7828 (Monday through Friday from 9:00 am to 5:30 pm EST)
Web site: http://www.epa.gov/owow/wetlands/

State, Nonprofit, and Private Organizations

Alliance for the Chesapeake Bay

The Alliance for the Chesapeake Bay is a private, nonprofit organization that recruits and mobilizes broad participation in restoration of the bay's resources, public policy, and education by providing citizens with the information and opportunities to make a difference at home, in their communities, and on a regional basis.

- The Alliance was chosen to manage the Small Watershed Grants program, developed by the Chesapeake Bay Program. This program was allocated $750,000 by Congress for grants to local governments and watershed-based nonprofit groups in the Chesapeake Bay drainage basin. In 1998 more than 160 organizations applied for the grants, and 37 were chosen. The major criterion for selection was that the project must have tangible results showing bay or river improvement that includes community involvement.

For more information, contact:
Alliance for the Chesapeake Bay
6600 York Road, Suite 100
Baltimore, MD 21212
Phone: (410) 377-6270 (or call the Chesapeake Regional Information Service (800) 662-CRIS)
Web site: http://www.acb-online.org

American Farmland Trust

The American Farmland Trust (AFT) was established as a nonprofit organization that works with farmers, business people, legislators, and conservationists to encourage sound farming practices and preserve the country's most critical agricultural resources.

- The Farm Legacy Program of the AFT encourages farm owners threatened by development to donate their lands to AFT. By donating their land, the landowners may retain lifetime use of the property because the AFT sells the farm with conservation easements to guarantee the preservation of the property. The AFT also accepts nonfarm properties and appreciated securities.

For more information, contact:
American Farmland Trust National Office
1920 N Street, N.W., Suite 400
Washington, D.C. 20036
Phone: (202) 659-5170
Fax: (202) 659-8339
Web site: http://www.farmland.org

California Coastal Conservancy

The California Coastal Conservancy was established by the California legislature to protect, restore, and enhance coastal resources by working in partnership with local governments, other public agencies, non-profit organizations, and private landowners.

The California Coastal Conservancy has done more than 700 projects along California's 1,110 mile coast-line and San Francisco Bay. The goals of the California Coastal Conservancy include:

- Improving public access to the coast and bay shores.
- Protecting and enhancing coastal wetlands, steams, and watersheds.
- Restoring urban waterfronts for public use and coastal development.
- Resolving coastal land use conflicts.
- Acquiring and holding environmentally valuable coastal land.
- Protecting agricultural lands.

For more information, contact:
California Coastal Conservancy
1330 Broadway, 11th Floor
Oakland, CA 94612
Phone: (510) 286-1015
Fax: (510) 286-0470
Web site: http://www.coastalconservancy.ca.gov/

California Waterfowl Association

The California Waterfowl Association (CWA) is a nonprofit organization that preserves, protects, and enhances California's waterfowl and wetland resources. The CWA provides technical assistance to landowners, conducts research, and lobbies state and federal governments to promote protection of waterfowl and provision of habitat.

- The Waterfowl Programs seek increases in populations of waterfowl, especially mallards, pintails, wood ducks, and Canada geese.
- Under the California Waterfowl Habitat Program, CWA assists the California Department of Fish and Game in providing incentive funds and preparing detailed plans for habitat management on private lands.
- A nontraditional effort involving salvage of eggs from nests destroyed by agricultural operations is being closely monitored to determine if released ducklings can assist waterfowl population enhancement efforts.

For further information, contact:
California Waterfowl Association
4630 Northgate Boulevard, Suite 150
Sacramento, CA 95834
Phone: (916) 648-1406
Fax: (916) 648-1665
Web site: http://www.calwaterfowl.org/

Chesapeake Bay Foundation

The Chesapeake Bay Foundation (CBF) is a nonprofit organization whose mission is to restore and sustain the bay's ecosystem by substantially improving water quality and productivity of the watershed.

- Restoration programs by CBF are voluntary and include citizens, school groups, and corporate participants. Examples of wetland restoration projects include wetland plantings, wetland mapping, and educational activities.

For more information, contact:
162 Prince George Street
Annapolis, MD 21401
Phone: (410) 268-8816
Fax: (410) 268-6687
Web site: http://www.cbf.org

Chesapeake Bay Trust

The Chesapeake Bay Trust is a nonprofit organization that promotes public awareness and participation in the restoration and protection of the Chesapeake Bay.

- The Trust was created by the Maryland General Assembly in 1985.
- More than 1,000 communities, volunteer groups, and schools in Maryland have received grant money totaling $933,287 for habitat restoration, cleanups, and other bay resource-related projects.
- The Trust is supported by private citizens and the business community. The purchase of Chesapeake Bay license plates funds part of the Trust. In addition, taxpayers may make donations of their refund to the Trust.

For further information, contact:
Chesapeake Bay Trust
60 West Street, Suite 200A
Annapolis, MD 21401
Phone: (410) 974-2941
Fax: (410) 269-0378
Web site: http://wwwchesapeakebaytrust.org

Ducks Unlimited

Ducks Unlimited (DU) is a private, nonprofit organization that works to help fulfill annual life cycle needs of waterfowl by protecting, enhancing, restoring, and managing important wetland and associated upland habitat throughout the states.

- DU cost-shares in the improvement of habitat through the Matching Aid to Restore States' Habitat (MARSH) Program. This reimbursement program provides matching funds for wetland acquisition and development.
- Habitat 2000: Campaign for a Continent - This is DU's six year comprehensive campaign to ensure a future for North America's wetlands and waterfowl. The program's goal is to restore 1.7 million acres of wetland and upland habitat by raising $600 million.

For further information, contact:
Ducks Unlimited National Headquarters
One Waterfowl Way
Memphis, TN 38120-2351
Phone: (901) 758-3825 or (800) 45-DUCKS
Web site: http://www.ducks.org

Great Plains Partnership

Spanning the 13 Great Plains states and the corresponding regions of Canada and Mexico, the Great Plains Partnership (GPP) is an outcome-oriented partnership composed of federal, state, and local agencies, tribes, nongovernmental organizations, and landowners. Its mission is to catalyze and empower the people of the Great Plains to define and create their own generational sustainable future.

- The GPP provides technical assistance and help in overcoming institutional and regulatory hurdles that local partnerships cannot resolve on their own.
- Sandhills (NE) - Ranchers in the Sandhills of Nebraska have been working with a local coordinator from the USFWS to preserve and restore wetlands areas that are important for hay meadows and fens, which are globally unique natural communities. Their coalition has grown to include representatives from other state and federal agencies. Their work provides an important example of successful cooperation.
- Rainwater Basin (NE) - The Rainwater Basin is a North American Waterfowl Management Plan Joint Venture in Nebraska to restore wetlands for migratory birds. GPP will test the use of a newly developed model that classifies wetland by functional value, in order to foster an alternative compliance strategy that allows farmers to develop a wetland restoration program through wetlands banking and trades to protect both the most valuable wetlands and croplands. Regulatory agencies, which will have to suspend current regulations, will be important partners and will oversee that the results equal or exceed those achievable through normal enforcement.

For more information, contact:
Great Plains Partnership
Web site: http://www.npwrc.usgs.gov

Illinois Wetlands Conservation Strategy

The Illinois Wetlands Conservation Strategy (IWCS) is a comprehensive plan to guide the development and implementation of Illinois's wetland programs and protection initiatives. It is an organizational tool used to identify opportunities for making programs work better. The goal of the IWCS is to ensure that there will be no net loss of wetlands or their functions in Illinois.

For further information, contact:
Illinois Wetlands Conservation Strategy
15536 Sr. 78
Havana, IL 62644
Web site: http://www.inhs.uiuc.edu/chf/pub/surveyreports/jul-aug95/wetland.html

Iowa River Corridor Project

The Iowa River Corridor Project uses a voluntary approach to wetland restoration by giving landowners economic alternatives for frequently flooded farmland, and the project is intended to improve water quality and wildlife habitat. It is sponsored by the Iowa NRCS. The farmers can choose to continue farming as they have, sell an easement and have a wetland restored, sell an easement and title to the USFWS, or try some alternative farming practices.

For further information, contact:
Iowa River Corridor Project
Web site: http://www.fws.gov/midwest/IowaRiverCorridor/

Izaac Walton League of America

The mission of the Izaac Walton League of America (IWLA) is to protect the nation's soil, air, woods, waters, and wildlife.

- The Wetlands Conservation and Sustainability Project, part of the Save Our Streams Program, helps bring citizens, planners, government agencies, businesses, and others together to become wetland stewards by taking a proactive role in wetland conservation and protection. The IWLA has lobbied at the national level to create and protect wetland legislation, and League members have worked for wetland protection and restoration through 350 local chapters nationwide.

For further information, contact:
Izaac Walton League of America National Office
707 Conservation Lane
Gaithersburg, MD 20878
Phone: (301) 548-0150
Fax: (301) 548-0146
Web site: http://www.iwla.org

Land Trust Alliance

The Land Trust Alliance supports conservation in communities across the country by ensuring that people who work through voluntary land trust organizations have the information, skills, and resources they need to save land.

- Land trusts are used to acquire land and then either transfer it to a governmental agency or retain it for long-term ownership and stewardship.
- Conservation easements are the principle tool used by most land trusts to achieve their land conservation objectives.
- There are currently more than 1,100 land trusts in America, including many for wetlands.

For more information, contact:
Land Trust Alliance
1319 F Street, NW, Suite 501
Washington, DC 20004
Phone: (202) 638-4725
Fax: (202) 638-4730
Web site: http://www.lta.org/

Michigan Wildlife Conservancy

The Michigan Wildlife Conservancy provides technical and financial assistance that landowners and managers need to restore and maintain wildlife habitat through cost-effective projects.

For more information, contact:
Michigan Wildlife Habitat Conservancy
Web site: http://www.miwildlife.org

National Audubon Society

The mission of the National Audubon Society (NAS) is to conserve and restore natural ecosystems, focusing on birds and other wildlife for the benefit of humanity and the earth's biological diversity.

- One of the high-priority campaigns of the NAS is to preserve wetlands. The goal of the Wetlands Campaign is to preserve and restore the nation's wetland ecosystems through a partnership of Audubon volunteer leaders, staff, and directors to protect birds, other wildlife, and their habitats, as well as to protect human health and safety and to sustain a healthy economy. The campaign includes a community-based effort to protect and restore 1,000,000 wetland acres within 3 years, establishment of strong wetland protection and restoration laws, creation of a network of thousands of Audubon volunteers and chapters, working together to promote sound measures to manage and protect wetland ecosystems, and public communication and education.

For more information, contact:
National Audubon Society
700 Broadway
New York, NY 10003
Phone: (212) 979-3000
Web site: http://www.audubon.org/

National Fish and Wildlife Foundation

The National Fish and Wildlife Foundation (NFWF) is a nonprofit organization established by Congress in 1984 to foster cooperative efforts to conserve fish, wildlife, and plant species. Its mission is to provide creative and sustainable solutions for fish and wildlife, and plant conservation. All NFWF grants are a two-to-one match (non-federal to federal), and the match must be derived from a source other than the applicant.

NFWF projects include education projects about fish, wildlife, plants, and habitats for schoolchildren, higher education institutions, and professionals. The organization is involved in fisheries conservation and management, neotropical migratory bird conservation, wetlands and private lands, and wildlife and habitat.

For more information, contact:
National Fish and Wildlife Foundation
1120 Connecticut Avenue, NW, Suite 900
Washington, DC 20036
Phone: (202) 857-0166
Fax: (202) 857-0162
Web site: http://www.nfwf.org

National Wildlife Federation

The mission of the National Wildlife Federation (NWF) is to educate, inspire, and assist individuals and organizations of diverse cultures to conserve wildlife and other natural resources and to protect the earth's environment in order to achieve a peaceful, equitable, and sustainable future.

The NWF's main goal is to raise awareness and involve people of all ages in their fight to conserve and protect the environment.

For further information, contact:
National Wildlife Federation
8925 Leesburg Pike
Vienna, VA 22184
Phone: (703) 790-4000
Web site: http://www.nwf.org

National Wetlands Conservation Alliance

The National Wetlands Conservation Alliance is an informal partnership of private organizations and government agencies working to build broad support for and to improve the delivery of voluntary landowner wetlands restoration, enhancement, and conservation.

- The organization's vision is to become informed landowners voluntarily deciding to protect and manage existing wetlands and restore and enhanced drained and partially drained wetlands.
- Funding and program guidance are provided by participating organizations and government agencies and the National Association of Conservation Districts.
- A major emphasis of the organization is to support and improve USDA's Wetland Reserve Program, Conservation Reserve Program, and other "Farm Bill" programs, and the Fish and Wildlife Service's Partners for Wildlife and North American Waterfowl Management Plan programs.

For further information, contact:
National Wetlands Conservation Alliance
509 Capitol Court, NE
Washington, DC 20002-4946
Phone: (202) 547-6223
Fax: (202) 547-6450
Web site: http://www.erols.com/wetlandg

Nebraska Environmental Trust

The Nebraska Environmental Trust Fund was organized in 1992 as a means to raise money for Nebraska's environment. What is unique about this program is that it is funded by the Nebraska Lottery. The public is also involved in the state's environment because the fund is administered by a governor-appointed board of nine citizens and six state agency representatives.

- One of the major focuses of the trust fund is the preservation and restoration of wetlands and other areas critical to rare or endangered species.
- Applicants that receive grant money must meet economic, technical, and financial feasibility criteria and show that the public benefits of the proposed project will be as apparent as the environmental benefits.

For more information, contact:
Nebraska Environmental Trust Fund
2200 North 33rd Street, P.O. Box 3070
Lincoln, NE 68503-0370
Phone: (402) 471-5409
Web site: http://www.environmentaltrust.org

Operation Green Stripe

Operation Green Stripe was developed in 1992 to combat the problem of surface water runoff of soil sediment by encouraging the planting of grassy buffer strips along streams, lakes, and sinkholes on farm property.

- Through Operation Green Stripe, Future Farmers of America (FFA) chapters recruit farmers to establish vegetative buffers between their fields and surface water supplies. Cooperating agriculture retailers provide free grass seed for the strips, and Monsanto provides educational grants to FFA chapters based on the number of farmers the students recruit.

For further information, contact:
Monsanto Company
800 North Lindbergh Boulevard
St. Louis, MO 63167
Phone: (314) 694-2789
Fax: (314) 694-2922
Web site: http://www.monsanto.com

Pheasants Forever

Pheasants Forever (PF) is a nonprofit wildlife conservation group whose mission is to protect and enhance pheasant and other wildlife populations throughout North America through public awareness and education, habitat restoration, development and maintenance, and improvements in land and water management policies. Local PF chapters work with private landowners to provide for the creation and enhancement of wildlife habitat.

- Since its establishment, PF has spent more than $24 million on habitat restoration projects on 850,000 acres of land. These projects restore habitat by renovating nesting cover, planting windbreaks and hedgerows, establishing food plots, restoring wetlands, and acquiring lands.

For further information, contact:
Pheasants Forever National Headquarters
1783 Buerkle Circle
St. Paul, MN 55110
Phone: (612) 773-2000
Fax: (612) 773-5500
Web site: http://www.pheasantsforever.org

Public Service Electric & Gas Co.

The Public Service Electric & Gas Co. (PSE&G) is a leader in providing energy-efficient services and developing environmentally sound energy systems to improve the social, economic, and environmental standards of society.

- PSE&G is conducting the Estuary Enhancement Program (EEP) under the New Jersey Department of Environmental Protection and the Delaware Department of Natural Resources and Environmental Control. Of the land slated for restoration, 12,500 acres are in New Jersey, and 8,000 are in Delaware. Nearly 17,000 acres are going to be restored as salt marshes, creating the largest endeavor of its kind. PSE&G purchased land and made agreements with landowners to gain access to land.

For more information, contact:
Public Service Enterprise Group (PSE&G)
Englewood, NJ 07631
Phone: 800-350-PSEG
Web site: http://www.pseg.com

Quail Unlimited

Quail Unlimited is a nonprofit organization that was established in 1981 to improve and preserve upland game habitat. It has more than 400 chapters. QU funds are used for local habitat and education projects, state wildlife departments, upland game bird management, habitat research, and education programs.

- One of QU's habitat improvement initiatives is to create water sites in arid and semiarid areas for quail habitat. Much of the water site development work is performed in cooperation with the Forest Service and the Bureau of Land Management under cost-share agreements.

For further information, contact:
Quail Unlimited National Headquarters
P.O. Box 610
Edgefield, SC 29824
Phone: (803) 637-5731, ext. 28
Web site: http://www.qu.org

Restore America's Estuaries

Restore America's Estuaries (RAE) is a nonprofit coalition of community-based organizations working to save coastal resources. Its mission is to protect and restore coastal areas by increasing awareness and appreciation of the resources and leading a campaign to restore 1 million acres of estuarine habitat (including wetlands) by the year 2010.

- RAE's 11 members are American Littoral Society (Hudson-Raritan estuaries of New York and New Jersey), Chesapeake Bay Foundation, Coalition to Restore Coastal Louisiana, Conservation Law Foundation (Gulf of Maine), Galveston Bay Foundation; North Carolina Coastal Federation, North Carolina Coastal Federation, People for Puget Sound, Save San Francisco Bay Association; Save the Bay (Narragansett Bay), Save the Sound (Long Island Sound), and Tampa BAYWATCH.
- Estuary habitat restoration includes maintaining food supplies for aquatic life, creating and protecting jobs that rely on estuaries (fishing, tourism, boating), protecting human health, expanding recreational abilities, enhancing quality of life, and education.

For more information, contact:
Restore America's Estuaries
1200 New York Avenue, N.W.
Suite 400
Washington, DC 20005
Phone: (202) 289-2380
Fax: (202) 842-4932
Web site: http://www.estuaries.org

Sierra Club

The Sierra Club is a nonprofit organization that promotes conservation of the natural environment by influencing public policy decisions.

More information about wetlands is available from the Sierra Club's wetlands website at http://www.sierraclub.org/wetlands

For information on the Sierra Club, contact:
Sierra Club
85 Second Street, Second Floor
San Francisco, CA 94105-3441
Phone: (415) 977-5500
Fax: (415) 977-5799
Web site: http://www.sierraclub.org/

The Tahoe Conservancy

The Tahoe Conservancy, a California agency, is charged with preserving and enhancing the unique ecological and recreational values of the Tahoe basin through the Tahoe Conservancy Program. Its primary objectives goals are to protect the natural environment of the basin, to increase public access and recreation opportunities for visitors to the lake, and to preserve and enhance the broad diversity of wildlife habitat in the Tahoe Basin.

- The Conservancy's work with private owners of wetland property comes primarily through its acquisition program. It focuses on obtaining conservation easements, development rights, and full titles to lands that contain marsh, meadow, or riparian areas. The Conservancy offers 95 percent of what property would bring on the open market.

For further information, contact:
The Tahoe Conservancy
2161 Lake Tahoe Boulevard
South Lake Tahoe, CA 96150
Phone: (916) 542-5580
Fax: (916) 542-5591
Web site: http://www.tahoecons.ca.gov/

The Nature Conservancy

The Nature Conservancy's (TNC) mission is to preserve plants, animals, and natural communities that represent the diversity of life on earth by protecting the lands and water they need to survive.

- The Natural Areas Registries program of the TNC honors private landowners of outstanding natural areas for their commitment to the survival of the land's natural heritage. The registry is voluntary, and no payment is involved.

For more information, contact:
The Nature Conservancy, International Headquarters
1815 North Lynn Street
Arlington, VA 22209
Phone: (703) 841-5300
Web site: http://nature.org

Trout Unlimited

Trout Unlimited (TU) is an organization of conservation-minded anglers who promote quality trout and salmon fisheries for their intrinsic values, as well as a reminder of watershed health. TU conserves, protects, and restores North America's trout and salmon fisheries and their watersheds. This is accomplished on the local, state, and national level.

For more information, contact:
Trout Unlimited
1500 Wilson Boulevard, Suite 310
Arlington, VA 22209-2404
Phone: (703) 522-0200
Fax: (703) 284-9400
Web site: http://www.tu.org

Wetland Habitat Alliance of Texas

The Wetland Habitat Alliance of Texas (WHAT) is an organization dedicated to preserving Texas wetlands by raising public awareness and appreciation of wetlands and funding projects to manage wetland waters; protect, enhance, and restore natural wetlands; and create wetlands on non-wetland sites.

- The cooperator and WHAT agree to a proposed project, and NRCS verifies the operable conditions before the project is approved. Interested landowners can receive up to 100 percent financial assistance for a 10-year minimum agreement.

For more information, contact:
Wetland Habitat Alliance of Texas
118 East Hospital, Suite 208
Nachodoches, TX 75961
Phone: (409) 569-9428 or (800) 962-WHAT
Web site: http://www.whatduck.org/homepage.htm

Wildlife Habitat Council

The Wildlife Habitat Council seeks to increase the quality of wildlife habitat on corporate, private, and public lands.

- WHC's Corporate Wildlife Habitat Certification/International Accreditation Program recognizes corporate properties with meaningful wildlife habitat management programs, including environmental education programs. Certification through WHC provides third-party credibility and an objective evaluation of projects.
- WHC builds cooperative ventures between corporate, private, government, and conservation communities to improve and manage habitat along river corridors and watersheds.
- Under its Wastelands to Wetlands program, WHC reclaims sites considered unsalvageable for wildlife habitat.

For further information, contact:
Wildlife Habitat Council
1010 Wayne Avenue, Suite 920
Silver Spring, MD 20910
Phone: (301) 588-8994
Fax: (301) 588-4629
Web site: http://www.wildlifehc.org/

Appendix B
U.S. Environmental Protection Agency Contacts

This appendix provides wetlands contacts, nonpoint source regional contacts, and Clean Water State Revolving Fund Contacts.

U.S. Environmental Protection Agency Contacts

EPA is grouped into 10 Regions. For questions about a particular state, contact the appropriate EPA Regional Coordinator listed below.

EPA Region	Wetland Contact	Nonpoint Source Regional Coordinators	Clean Water State Revolving Fund Regional Coordinators
Region 1: CT, MA, ME, NH, RI, VT http://www.epa.gov/region01/	U.S. EPA-Region 1 Wetlands Protection Unit One Congress Street Boston, MA 02114-2023 http://www.epa.gov/region01/topics/ecosystems/wetlands.html	U.S. EPA-Region 1 Nonpoint Source Coordinator One Congress Street, Boston, MA 02114-2023 http://www.epa.gov/region01/topics/water/npsources.html	U.S. EPA-Region 1 SRF Program Contact One Congress Street Boston, MA 02114-2023 http://www.epa.gov/ne/cwsrf/index.html
Region 2: NJ, NY, PR, VI http://www.epa.gov/Region2	U.S. EPA-Region 2 Water Programs Branch Wetlands Section 290 Broadway New York, NY 10007-1866 http://www.epa.gov/region02/water/wetlands/	U.S. EPA-Region 2 Water Programs Branch Nonpoint Source Coordinator 290 Broadway New York, NY 10007-1866 http://www.epa.gov/region02/water/npspage.htm	U.S. EPA-Region 2 Water Programs Branch SRF Program Contact 290 Broadway New York, NY 10007-1866 http://www.epa.gov/Region2/water/wpb/staterev.htm
Region 3: DC, DE, MD, PA, VA, WV http://www.epa.gov/region03	U.S. EPA-Region 3 Wetlands Protection Section 1650 Arch Street (3WP12) Philadelphia, PA 19103 http://www.epa.gov/reg3esd1/hydricsoils/index.htm	U.S. EPA-Region 3 Nonpoint Source Coordinator 1650 Arch Street (3WP12) Philadelphia, PA 19103 http://www.epa.gov/reg3wapd/nps/	U.S. EPA-Region 3 Construction Grants Branch SRF Program Contact 1650 Arch Street (3WP12) Philadelphia, PA 19103 http://www.epa.gov/reg3wapd/srf/index.htm
Region 4: AL, FL, GA, KY, MS, NC, SC, TN http://www.epa.gov/region4/	U.S. EPA-Region 4 Wetlands Section 61 Forsyth Street, SW Atlanta, GA 30303 http://www.epa.gov/region4/water/wetlands/	U.S. EPA-Region 4 Nonpoint Source Coordinator 61 Forsyth Street, SW Atlanta, GA 30303 http://www.epa.gov/region4/water/nps/	U.S. EPA-Region 4 Surface Water Permits & Facilities SRF Program Contact 61 Forsyth St. Atlanta GA, 30303 http://www.epa.gov/Region4/water/gtas/grantprograms.html
Region 5: IL, IN, MI, MN, OH, WI http://www.epa.gov/region5/	U.S. EPA-Region 5 Watersheds and Wetlands Water Division (W-15J) 77 West Jackson Blvd. Chicago, IL 60604 http://www.epa.gov/region5/water/wshednps/topic_wetlands.htm	U.S. EPA-Region 5 Nonpoint Source Coordinator Water Division (W-15J) 77 West Jackson Blvd. Chicago, IL 60604 http://www.epa.gov/region5/water/wshednps/topic_nps.htm	U.S. EPA-Region 5 SRF Program Contact Water Division (W-15J) 77 West Jackson Blvd. Chicago, IL 60604 http://www.epa.gov/region5/business/fs-cwsrf.htm

EPA Region	Wetland Contact	Nonpoint Source Regional Coordinators	Clean Water State Revolving Fund Regional Coordinators
Region 6: AR, LA, NM, OK, TX http://www.epa.gov/region6	U.S. EPA-Region 6 Marine and Wetlands Section 1445 Ross Ave., Suite 1200 Dallas, TX 75202 http://www.epa.gov/region6/water/ecopro/index.htm	U.S. EPA-Region 6 Nonpoint Source Coordinator 1445 Ross Ave., Suite 1200 Dallas, TX 75202 http://www.epa.gov/region6/water/ecopro/watershd/nonpoint/	U.S. EPA-Region 6 SRF Program Contact 1445 Ross Ave., Suite 1200 Dallas, TX 75202 http://www.epa.gov/Arkansas/6en/xp/enxp2c4.htm
Region 7: IA, KS, MO, NE http://www.epa.gov/region7	U.S. EPA-Region 7 Wetlands Protection Section (ENRV) 901 N. 5th St. Kansas City, KS 66101 http://www.epa.gov/region7/wetlands/index.htm	U.S. EPA-Region 7 Nonpoint Source Coordinator 901 N. 5th St. Kansas City, KS 66101	U.S. EPA-Region 7 SRF Program Contact 901 N. 5th St. Kansas City, KS 66101 http://www.epa.gov/Region7/water/srf.htm
Region 8: CO, MT, ND, SD, UT, WY http://www.epa.gov/region8	U.S. EPA-Region 8 Wetlands Program 999 18th Street, Suite 500 Denver, CO 80202-2405 http://www.epa.gov/region8/water/wetlands/wetlands.html	U.S. EPA-Region 8 Nonpoint Source Coordinator 999 18th Street, Suite 300 Denver, CO 80202-2405 http://www.epa.gov/region8/water/nps/contacts.html	U.S. EPA-Region 8 SRF Program Contact 999 18th Street, Suite 300 Denver, CO 80202-2405
Region 9: AZ, CA, HI, NV, Pacific Islands http://www.epa.gov/region9/	U.S. EPA-Region 9 Water Division, Wetlands 75 Hawthorne Street San Francisco, CA 94105 http://www.epa.gov/region09/water/wetlands/index.html	U.S. EPA-Region 9 Nonpoint Source Coordinator 75 Hawthorne Street San Francisco, CA 94105 http://www.epa.gov/region09/water/nonpoint/index.html	U.S. EPA-Region 9 Construction Grants Branch SRF Program Contact 75 Hawthorne Street San Francisco, CA 94105 http://www.epa.gov/region9/funding/
Region 10: AK, ID, OR, WA http://www.epa.gov/region10/	U.S. EPA-Region 10 Wetlands Section 1200 Sixth Ave. Seattle, WA 98101 http://yosemite.epa.gov/R10/ECOCOMM.NSF/webpage/Wetlands	U.S. EPA-Region 10 Nonpoint Source Coordinator 1200 Sixth Ave. Seattle, WA 98101	U.S. EPA-Region 10 Ecosystems & Communities SRF Program Contact 1200 Sixth Ave. Seattle, WA 98101 http://yosemite.epa.gov/r10/ecocomm.nsf/webpage/Clean+Water+State+Revolving+Fund+in+Region+10
General Program Information	U.S. EPA Wetlands Division (4502F) Mail Code RC-4100T 1200 Pennsylvania Ave., NW Washington, DC 20460 http://www.epa.gov/owow/wetlands/	U.S. EPA Nonpoint Source Control Branch (4503-T) Ariel Rios Bldg. 1200 Pennsylvania Ave., NW Washington, DC 20460 http://www.epa.gov/owow/nps	U.S. EPA The Clean Water State Revolving Fund Branch (4204M) 1201 Constitution Ave., NW Washington, DC 20004 http://www.epa.gov/owm/cwfinance/cwsrf/index.htm