CHAPTER 6: Management Measures for Hydromodification: Channelization and Channel Modification, Dams, and Streambank and Shoreline Erosion

I. INTRODUCTION

A. What "Management Measures" Are

This chapter specifies management measures to protect coastal waters from sources of nonpoint pollution related to hydromodification activities. "Management measures" are defined in section 6217 of the Coastal Zone Act Reauthorization Amendments of 1990 (CZARA) as economically achievable measures to control the addition of pollutants to our coastal waters, which reflect the greatest degree of pollutant reduction achievable through the application of the best available nonpoint pollution control practices, technologies, processes, siting criteria, operating methods, or other alternatives.

These management measures will be incorporated by States into their coastal nonpoint programs, which under CZARA are to provide for the implementation of management measures that are "in conformity" with this guidance. Under CZARA, States are subject to a number of requirements as they develop and implement their Coastal Nonpoint Pollution Control Programs in conformity with this guidance and will have some flexibility in doing so. The application of these management measures by States to activities causing nonpoint pollution is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA).

B. What "Management Practices" Are

In addition to specifying management *measures*, this chapter also lists and describes management *practices* for illustrative purposes only. While State programs are required to specify management *measures* in conformity with this guidance, State programs need not specify or require the implementation of the particular management *practices* described in this document. However, as a practical matter, EPA anticipates that the management measures generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. 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 has also used some of these practices, or appropriate combinations of these practices, as a basis for estimating the effectiveness, costs, and economic impacts of achieving the management measures. (Economic impacts of the management measures are addressed in a separate document entitled *Economic Impacts of EPA Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters.*)

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 list of practices for each management measure is not all-inclusive and does not preclude States or local agencies from using other technically sound practices. In all cases, however, the practice or set of practices chosen by a State needs to achieve the management measure.

C. Scope of This Chapter

This chapter addresses three categories of sources of nonpoint pollution from hydromodification activities that affect coastal waters:

(1) Channelization and channel modification;
(2) Dams; and
(3) Streambank and shoreline erosion.

Each category of management measures is addressed in a separate section of this guidance. Each section contains (1) the management measure; (2) an applicability statement that describes, when appropriate, specific activities and locations for which the measure is suitable; (3) a description of the management measure's purpose; (4) the basis for the management measure's selection; (5) information on management practices that are suitable, either alone or in combination with other practices, to achieve the management measure; (6) information on the effectiveness of the management measure and/or of practices to achieve the measure; and (7) information on costs of the measure and/or practices to achieve the measure.

D. Relationship of This Chapter to Other Chapters and to Other EPA Documents

1. Chapter 1 of this document contains detailed information on the legislative background for this guidance, the process used by EPA to develop this guidance, and the technical approach used by EPA in the guidance.

2. Chapter 7 of this document contains management measures to protect wetlands and riparian areas that serve an NPS pollution abatement function. These measures apply to a broad variety of sources, including sources related to hydromodification activities.

3. Chapter 8 of this document contains information on recommended monitoring techniques to (1) ensure proper implementation, operation, and maintenance of the management measures and (2) assess over time the success of the measures in reducing pollution loads and improving surface water quality.

4. EPA has separately published a document entitled *Economic Impacts of EPA Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters.*

5. NOAA and EPA have jointly published guidance entitled *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance.* This guidance contains details on how State Coastal Nonpoint Pollution Control Programs are to be developed by States and approved by NOAA and EPA. It includes guidance on the following:

   - The basis and process for EPA/NOAA approval of State Coastal Nonpoint Pollution Control Programs;
   - How NOAA and EPA expect State programs to provide for the implementation of management measures" in conformity" with this management measures guidance;
   - How States may target sources in implementing their Coastal Nonpoint Pollution Control Programs;
   - Changes in State coastal boundaries; and
   - Requirements concerning how States are to implement the Coastal Nonpoint Pollution Control Programs.

II. CHANNELIZATION AND CHANNEL MODIFICATION MANAGEMENT MEASURES

One form of hydromodification is *channelization* or *channel modification.* These terms (used interchangeably) describe river and stream channel engineering undertaken for the purpose of flood control, navigation, drainage improvement, and reduction of channel migration potential (Brookes, 1990). Activities such as straightening, widening, deepening, or relocating existing stream channels and clearing or snagging operations fall into this category. These forms of hydromodification typically result in more uniform channel cross sections, steeper stream gradients, and reduced average pool depths.

The terms *channelization* and *channel modification* are also used in this chapter to refer to the excavation of borrow pits, canals, underwater mining, or other practices that change the depth, width, or location of waterways or embayments in coastal areas. Excavation of marina basins is addressed separately in Chapter 5 of this guidance.

The term *flow alteration* describes a category of hydromodification activities that result in either an increase or a decrease in the usual supply of fresh water to a stream, river, or estuary. Flow alterations include diversions, withdrawals, and impoundments. In rivers and streams, flow alteration can also result from undersized culverts, transportation embankments, tide gates, sluice gates, and weirs.

Levees along a stream or river channel are also addressed by this section. A *levee* is defined by the U.S. Army Corps of Engineers (USACE) as an embankment or shaped mound for flood control or hurricane protection (USACE, 1981). Pond banks, and other small impoundment structures, often referred to as levees in the literature, are not considered to be levees as defined in this section. Additionally, a *dike* is not used in this guidance to refer to the same structure as a levee, but rather is defined as a channel stabilization structure sited in a river or stream perpendicular to the bank.

For the purpose of this guidance, no distinction will be made between the terms *river* and *stream* because no definition of either could be found to quantitatively distinguish between the two. Likewise, no distinction will be made for word combinations of these two terms; for example, *streambank* and *riverbank* will be considered to be synonymous.

The following definitions for common terms associated with channelization activities apply to this chapter (USACE, 1983). Other definitions are provided in the Glossary at the end of the chapter.

> *Channel:* A natural or constructed waterway that continuously or periodically passes water.
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> *Channel stabilization:* Structures placed below the elevation of the average surface water level (lower bank) to control bank erosion or to prevent bank or channel failure.
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> *Streambank:* The side slopes of a channel between which the streamflow is normally confined.
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> *Lower bank:* The portion of the streambank below the elevation of the average water level of the stream.
>
> *Upper bank:* The portion of the streambank above the elevation of the average water level of the stream.
>
> *Streambank stabilization:* Structures placed on or near a distressed streambank to control bank erosion or to prevent bank failure.

Based on the above definitions, the difference between channel stabilization and streambank stabilization is that in streambank stabilization, the upper bank is also protected from erosion or failure. This additional protection guards against erosive forces caused by high-water events and by land-based causes such as runoff or improper siting of buildings. Levees are placed along streambanks to prevent flooding in adjacent areas during extreme high-water events.

Effects of Channelization and Channel Modification Activities

General Problematic Effects

Channel modification activities have deprived wetlands and estuarine shorelines of enriching sediments, changed the ability of natural systems to both absorb hydraulic energy and filter pollutants from surface waters, and caused interruptions in the different life stages of aquatic organisms (Sherwood et al., 1990). Channel modification activities can also alter instream water temperature and sediment characteristics, as well as the rates and paths of sediment erosion, transport, and deposition. A frequent result of channelization and channel modification activities is a diminished suitability of instream and riparian habitat for fish and wildlife. Hardening of banks along waterways has eliminated instream and riparian habitat, decreased the quantity of organic matter entering aquatic systems, and increased the movement of NPS pollutants from the upper reaches of watersheds into coastal waters.

Channel modification projects undertaken in streams or rivers to straighten, enlarge, or relocate the channel usually require regularly scheduled maintenance activities to preserve and maintain completed projects. These maintenance activities may also result in a continual disturbance of instream and riparian habitat. In some cases, there can be substantial displacement of instream habitat due to the magnitude of the changes in surface water quality, morphology and composition of the channel, stream hydraulics, and hydrology.

Excavation projects can result in reduced flushing, lowered dissolved oxygen levels, saltwater intrusion, loss of streamside vegetation, accelerated discharge of pollutants, and changed physical and chemical characteristics of bottom sediments in surface waters surrounding channelization or channel modification projects. Reduced flushing, in particular, can increase the deposition of finer-grained sediments and associated organic materials or other pollutants.

Levees may reduce overbank flooding and the subsequent deposition of sediment needed to nourish riverine and estuarine wetlands and riparian areas. Levees can cause increased transport of suspended sediment to coastal and near-coastal waters during high-flow events. Levees located close to streambanks can also prevent the lateral movement of sediment-laden waters into adjacent wetlands and riparian areas that would otherwise serve as depositories for sediment, nutrients, and other NPS pollutants. This has been a major factor, for example, in the rapid loss of coastal wetlands in Louisiana (Hynson et al., 1985). Levees also interrupt natural drainage from upland slopes and can cause concentrated, erosive flows of surface waters.

The resulting changes to the distribution, amount, and timing of flows caused by flow alterations can affect a wide variety of living resources. 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 crustaceans. 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.

Specific Effects

Depending on preproject site conditions and the extent of hydromodification activity, new and existing channelization and channel modification projects may result in no additional NPS problems, additional NPS problems, or benefits.

The following are major categories of channelization and channel modification effects and examples of associated problems and benefits.

Changed Sediment Supply. One of the more significant changes in instream habitat associated with channelization and channel modification projects is in sediment supply and delivery. Streamside levees have been linked to accelerated rates of erosion and decreased sediment supplies to coastal areas (Hynson et al., 1985). Sherwood and others (1990) evaluated the long-term impacts of channelization projects on the Columbia River estuary and found that changes to the river system resulted in a net increase of 68 million cubic meters of sediment in the estuary. These changes in sediment supply can include problems such as increased sedimentation to some areas (an estuary, for example) or decreased sediment to other areas (such as streamside wetlands or estuarine marshes). Other changes may be beneficial; for example, a diversion that delivers sediment to eroding marshes (Hynson et al., 1985). Another example of a beneficial channel stabilization project might be one that results in increased flushing and the elimination of unwanted sediment in the spawning area of a stream.

Reduced Freshwater Availability. Salinity above threshold levels is considered to be a form of NPS pollution in freshwater supplies. Reduced freshwater availability for municipal, industrial, or agricultural purposes can result from some channelization and channel modification practices. Similarly, alteration of the salinity regime in portions of a channel can result in ecological changes in vegetation in the streamside area. Diversion of fresh water by flood- and hurricane-protection levees has reduced freshwater inputs to adjacent marshes. This has resulted in increased marsh salinities and degradation of the marsh ecosystem (Hynson et al., 1985). A benefit of other diversion projects was a reduction of freshwater inputs to estuarine areas that were becoming too fresh because of overall increases in fresh water from changes in land use within a watershed. Increases in oyster harvests have been attributed to a freshwater diversion in Plaquemines Parish, Louisiana. Over the 6-year period from 1970 to 1976, oyster harvests increased by over 3.5 million pounds (Hynson et al., 1985). Potential problems with diversions include erosion, settlement, seepage, and liquefaction failure (Hynson et al., 1985).

Accelerated Delivery of Pollutants. Channelization and channel modification projects can lead to an increased quantity of pollutants and accelerated rate of delivery of pollutants to downstream sites. Alterations that increase the velocity of surface water or that increase flushing of the streambed can lead to more pollutants being transported to downstream areas at possibly faster rates. Urbanization has been linked to downstream channelization problems in Hawaii (Anderson, 1992). It is believed that the deterioration of Kaneohe Bay may be caused by development within the watershed, which has increased runoff flows to streams entering the Bay. Streams that once meandered and contained natural vegetation to filter out nutrient and sediment are now channelized and contain surface water that is rich in nutrients and other pollutants associated with urban areas (Anderson, 1992). Some excavation projects have resulted in poor surface water circulation along with increased sedimentation and other surface water quality problems within the excavated basin. In some of these cases, additional, carefully designed channel modifications can increase flushing rates, which deliver accumulated pollutants from the basin to points downstream that are able to assimilate or otherwise beneficially use the accumulated materials.

Loss of Contact with Overbank Areas. Instream hydraulic changes can decrease or interfere with surface water contact to overbank areas during floods or other high-water events. Channelization and channel modification activities that lead to a loss of surface water contact in overbank areas also may result in reduced filtering of NPS pollutants by streamside area vegetation and soils. Areas of the overbank that are dependent on surface water contact (i.e., riparian areas and wetlands) may change in character and function as the frequency and duration of flooding change. Erickson and others (1979) reported a major influence on wetland drainage in the Wild Rice Creek Watershed in North and South Dakota. Drainage rates from streamside areas were 2.6 times higher in the channelized area than in undisturbed areas during preliminary project activities and 5.3 times higher following construction. Schoof (1980) reported several other impacts of channelization, including drainage of wetlands, reduction of oxbows and stream meander, clearing of floodplain hardwood, lowering of ground-water levels, and increased erosion. Channel modification projects such as setback levees or compound channel design can provide the overbank flooding to areas needing it while also providing a desired level of flood protection to adjoining lands.

Changes to Ecosystems. Channelization and channel modification activities can lead to loss of instream and riparian habitat and ecosystem benefits such as pathways for wildlife migration and conditions suitable for reproduction and growth. Problematic flow modifications, for example, have resulted in reversal of flow regimes of some California rivers or streams, which has led to the disorientation of anadromous fish that rely on flow to direct them to spawning areas (James and Stokes Associates, Inc., 1976). Eroded sediment may deposit in new areas, covering benthic communities or altering instream habitat (Sherwood et al., 1990). Orlova and Popova (1976) researched the effects on fish population resulting from altering the hydrologic regime with hydraulic structures such as channels. The effects assessed by Orlova and Popova (1976) include:

- Deterioration of spawning habitat and conditions, resulting in lower recruitment of river species;
- Increases in stocks of summer spawning river species; and
- Changes in types and amounts of food organisms.

Many channel or streambank stabilization structures provide increased instream habitat for certain aquatic species. For example, Sandheinrich and Atchison (1986) reported increases in densities of epibenthic insects within revetments and stone dike areas and more suitable substrate for bottom-dwelling insects in revetment areas.

Instream and Riparian Habitat Altered by Secondary Effects. Secondary instream and riparian habitat alteration effects from channelization and channel modification projects include movement of estuarine turbidity maximum zones (zone of higher sediment concentrations caused by salinity and tide-induced circulation) with salinity changes, cultural eutrophication caused by inadequate flushing, and trapping of large quantities of sediment. Wolff and others (1989) analyzed the impacts of flow augmentation on the stream channel and instream habitat following a transbasin water diversion project in Wyoming. The South Fork of Middle Crow Creek, previously ephemeral, was beneficially used as a conveyance to create instream habitat as a part of impact management measures of the transbasin diversion project. Discontinuous channels, high summer water temperature, and flow interruptions and fluctuations were identified as potential limiting factors for the development of such practices for this particular project. Modeling results, however, indicated that as the channel develops, the effects of the first two limiting factors will be negligible. Following 2 years of increased flow in the 5.5-mile section of stream channel (reach) used in this study, the volume of stream channel had increased 32 percent and more channel areas were expected to develop on approximately 67 percent of the stream reach. The total area of beaver ponds had more than doubled. The brook trout with which the beaver ponds were stocked were reported to be surviving and growing.

The examples described above illustrate the range of possible effects that can result from channelization and channel modification projects. These effects can be either beneficial or problematic to the ecology and surrounding riparian habitat. The effects caused by changed sediment supplies provide an excellent example of these varying impacts. In one case, sediment supplies to coastal marshes are insufficient and the marshes are subsiding (problem). In another case, sediment supplies to an estuary are increasing to the point of causing changes to the natural tidal flow (problem). A final example showed decreased sediment in a streambed, which has resulted in better conditions for native spawning fish (benefit). Thus, depending on site-specific conditions and the particular channelization or channel modification practices used, the project will have positive or negative NPS pollution impacts.

Another confounding factor is the potential for one project to have multiple NPS problems and/or benefits. Assuming that a channelization or channel modification project was originally designed to overcome a specific problem (e.g., channel deepening for navigation, streambank stabilization for erosion control, or levee construction for flood control), the project was intended to be beneficial. Unfortunately, planners of many channelization and channel modification projects have, in the past, been myopic when considering the range of impacts associated with the project. The purpose of the management measures in this section is to recommend proper evaluation of potential projects and reevaluation of existing projects to reduce NPS impacts and maximize potential benefits.

Proper evaluation of channelization and channel modification projects should consider three major points.

(1) **Existing conditions.** New and existing channelization and channel modification projects should be evaluated for potential effects (both problematic and beneficial) based on existing stream and watershed conditions. Site-specific stream conditions, such as flow rate, channel dimensions, typical surface water quality, or slope, should be evaluated in conjunction with streamside conditions, such as soil and vegetation type, slopes, or land use. Characteristics of the watershed also need to be evaluated. This phase of the evaluation will identify baseline conditions for potential projects and can be compared to historical conditions for projects already in place.

(2) **Potential conditions**. Anticipated changes to the base (or existing) conditions in a stream, along the streambank, and within the watershed should be evaluated. By examining potential changes caused by new conditions, long-term impacts can be factored into the design or management of a channelization or channel modification project. Studies like that of Sandheinrich and Atchison (1986) clearly show that short-term benefits from hydromodification activities can change to long-term problems.

(3) **Watershed management**. Evaluation of changes in watershed conditions is paramount in the proper design of a channelization or channel modification project. Since the design of these projects is based on hydrology, changes in watershed hydrology will certainly impact the proper functioning of a channelization or channel modification structure. Additionally, many surface water quality changes associated with a channelization or channel modification project can be attributed to watershed changes, such as different land use, agricultural practices, or forestry practices.

The two management measures presented in this section of the chapter promote the evaluation of channelization and channel modification projects. Channels should be evaluated as a part of the watershed planning and design processes, including watershed changes from new development in urban areas, agricultural drainage, or forest clearing. The purpose of the evaluation is to determine whether resulting NPS changes to surface water quality or instream and riparian habitat can be expected and whether these changes will be good or bad.

Existing channelization and channel modification projects can be evaluated to determine the NPS impacts and benefits associated with the projects. Modifications to existing projects, including operation and maintenance or management, can also be evaluated to determine the possibility of improving some or all of the impacts without changing the existing benefits or creating additional problems.

In both new and existing channelization and channel modification projects, evaluation of benefits and/or problems will be site-specific. Mathematical models are one type of tool used to determine these impacts. Some models provide a simple analysis of a particular situation and are good for screening purposes. Other models evaluate complex interactions of many variables and can be powerful, site-specific evaluation tools. There are also structural and nonstructural practices that can be used to prevent either NPS pollution effects from or NPS impacts to channelization and channel modification projects. Interpretation of design changes, model results predicting changes or impacts, or the effects of structural or nonstructural practices requires sound biological and engineering judgment and experience.

The first three problems listed above are usually associated with the alteration of physical characteristics of surface waters. Accordingly, they are addressed by Management Measure II.A in the section below. The last three problems listed above can be grouped to represent problems resulting from modification of instream and riparian habitat. They are addressed by Management Measure II.B in the subsequent section below.

A. Management Measure for Physical and Chemical Characteristics of Surface Waters

(1) Evaluate the potential effects of proposed channelization and channel modification on the physical and chemical characteristics of surface waters in coastal areas;

(2) Plan and design channelization and channel modification to reduce undesirable impacts; and

(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.

1. Applicability

This management measure is intended to be applied by States to public and private channelization and channel modification activities in order to prevent the degradation of physical and chemical characteristics of surface waters from such activities. This management measure applies to any proposed channelization or channel modification projects, including levees, 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. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with management measures and will have some flexibility in doing so. The application of this management measure by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

The purpose of this 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 the proposed work. Implementation of this management measure is intended to occur concurrently with the implementation of Management Measure B (Instream and Riparian Habitat Restoration) of this section. For existing projects, the purpose of this management measure is to ensure that 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 sediment, turbidity, salinity, temperature, nutrients, dissolved oxygen, oxygen demand, and contaminants.

Implementation of this management measure in the planning process for new projects will require a two-pronged approach:

(1) Evaluate, with numerical models for some situations, the types of NPS pollution related to instream changes and watershed development.

(2) Address some types of NPS problems stemming from instream changes or watershed development with a combination of nonstructural and structural practices.

The best available technology that can be applied to examine the physical and chemical effects of hydraulic and hydrologic changes to streams, rivers, or other surface water systems are models and past experience in situations similar to those described in the case studies discussed in this chapter. These models, discussed in detail under the practices of this section, 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 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, levee protection, channel stabilization, flow restrictors, check dam systems, grade control structures, vegetative cover, instream sediment control, noneroding roadways, and setback levees or flood walls. 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 and possibly corrected.

This management measure addresses three of the effects of channelization and channel modification that affect the physical and chemical characteristics of surface waters:

(1) Changed sediment supply;
(2) Reduced freshwater availability; and
(3) Accelerated delivery of pollutants.

3. Management Measure Selection

Selection of this management measure was based on the following factors:

(1) Published case studies of existing channelization and channel modification projects describe alterations to the physical and chemical characteristics of surface waters (Burch et al., 1984; Erickson et al., 1979; Parrish et al., 1978; Pennington and Dodge, 1982; Petersen, 1990; Reiser et al., 1985; Roy and Messier, 1989; Sandheinrich and Atchison, 1986; Sherwood et al., 1990). Frequently, the postproject conditions are intolerable to desirable fish and wildlife.

(2) 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, 1981; USACE, 1989).

(3) Increased volumes of runoff resulting from some types of watershed development produce hydraulic changes in downstream areas including bank scouring, channel modifications, and flow alterations (Anderson, 1992; Schueler, 1987).

4. Practices

As explained more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require implementation of practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

▨ *a. 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.*

Mathematical Models for Physical and Chemical Characteristics of Surface Waters, Including Instream Flows

Over the past 20 to 30 years, theoretical and engineering advances have been made in the quantitative descriptions and interactions of physical transport processes; sediment transport, erosion, and deposition; and surface water quality processes. Based on these theoretical approaches and the need for evaluations of proposed surface water resource engineering projects, a variety of simulation models have been developed and applied to provide technical input for complex decision-making. 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.

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. Because of the increasing availability of relatively inexpensive computer hardware and software over the past decade, rapid advances have been made in the development of sophisticated two-dimensional (2D) and three-dimensional (3D) time-variable hydrodynamic models that can be used for environmental assessments of hydromodification projects (see Spaulding, 1990; McAnally, 1987). Two-dimensional depth or laterally averaged hydrodynamic models are economical and can be routinely developed and applied for 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, usually considered more of an academic research tool, 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).

The necessity for the application of detailed 2D and 3D hydrodynamic models for large-scale hydromodification projects can be demonstrated using detailed simulation models to hindcast the long-term surface water quality and ecological impact of projects that have actually been constructed over the past 20 to 40 years. Sufficient data are available from a number of large-scale hydromodification projects in the United States and overseas that can provide data sets for the development of hindcasting models to illustrate the capability of the models to simulate the known adverse long-term ecological consequences of projects that have actually been operational for decades. The results of such hindcasting evaluations could provide important guidance for resource managers, who use good professional judgment to understand the level of technical complexity and the costs required for an adequate assessment of the long-term ecological impacts of proposed hydromodification projects. In the Columbia River estuary, for example, Sherwood and others (1990) used historical bathymetric data with a numerical 2D hydrodynamic model (Hamilton, 1990) to document the long-term impact of hydromodification changes on channel morphology, riverflow transport processes, salinity intrusion, residence time, and net accumulation of sediment.

When models are not suited to evaluate a particular situation, examining existing conditions and using best professional judgment are another way to evaluate the effects of hydromodification activities. For example, in cases where water supplies need to be restored to wetlands that have historically experienced a loss of water contact, models can be used to ensure that the length of time of renewed water exposure is within the tolerance of the wetland plants for inundation, since excessive inundation of wetland plants can be as destructive as loss of water contact. Surface water quality monitoring and procedures such as Rapid Bioassessment Protocols (see Management Measure B in this section for more information) are examples of methods to examine existing conditions.

Table 6-1 lists some of the available models for studying the effects of channelization and channel modification activities. Listed below are examples of channelization and channel modification activities and associated models that can be used in the planning process.

- **Impoundments.** A hydrodynamic model coupled with a surface water quality model (e.g., WASP4) can be applied to determine changes in surface water quality due to an increased detention of storm water runoff caused by the upstream dams. Changes in sediment distribution in the estuary caused by a reduction in the sediment source (due to the trap efficiency of an upstream impoundment) are difficult to determine with modeling.

- **Tidal Flow Restrictions.** Restrictions of tidal flow may include undersized culverts and bridges, tide gates, and weirs. One potential modeling technique to determine the flow through the restriction is the USGS FESWMS-2DH model. Once the flows through the restriction are defined, then WASP4 can be applied to compute surface water quality impacts.

- **Breakwaters, Jetties, and Wave Barriers.** Construction of these coastal structures may alter the surface water circulation patterns and cause sediment accumulation. Physical hydraulic models can be used to qualitatively determine where sediment will accumulate, but they cannot reliably determine the quantities of accumulated sediment. Finite element (CAFE) or finite difference (EFDC) models can be used to determine changes in circulation/flushing caused by the addition or modification of coastal structures. The WASP4 model can be applied to determine surface water quality impacts.

- **Flow Regime Alterations.** Removing or increasing freshwater flows to an estuary can alter the hydraulic characteristics and water chemistry. The WASP4 model can be used to determine surface water quality impacts.

- **Excavation of Uplands for Marina Basins or Lagoon Systems.** Depending on the magnitude and frequency of water-level fluctuations, this activity may result in poorly flushed areas within a marina or lagoon system. Finite element or finite difference models (e.g., CAFE/DISPER and EFDC) can be used to determine a design that will result in adequate flushing. The WASP4 model can be applied to determine surface water quality (e.g., dissolved oxygen or salinity) impacts.

Model Selection

Although a wide range of adequate hydrodynamic and surface water quality models are available, the central issue in the selection of appropriate models for an evaluation of a specific hydromodification project 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 marina project with planned excavation of an upland area 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—requiring less time and money—would most likely be sufficient (McPherson, 1991). In contrast, substantial technical assessment of the 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.

Table 6-1. Models Applicable to Hydromodification Activities

Model	Description	Source and Contact
CAFE	Circulation Analysis Finite Element.	Developed at MIT in mid-1970s by J.D. Wang and J.J. Connor. E. Eric Adams Massachusetts Institute of Technology Department of Civil Engineering Cambridge, MA
DISPER	Dispersion analysis model that is coupled to the CAFE model.	Developed at MIT in mid-1970s by G.C. Christodoulou. E. Eric Adams Massachusetts Institute of Technology Department of Civil Engineering Cambridge, MA
TABS-2	Generalized numerical modeling system for open-channel flows, sedimentation, and constituent transport.	Developed by U.S. Army Corps of Engineers Waterways Experiment Station 1978-1984. U.S. Army Waterways Experiment Station Hydraulics Laboratory P.O. Box 631 Vicksburg, MS 39180-0631
EFDC	Environmental Fluid Dynamics Code. This is a 3D finite-difference hydrodynamic and salinity model.	Developed by John Hamrick at the Virginia Institute of Marine Science 1990-1991. Dr. John Hamrick 9 Sussex Court Williamsburg, VA 23188
WASP4	Water Quality Analysis Simulation Program. Simulates dissolved oxygen and nutrients.	Developed and updated by EPA Environmental Research Laboratory, Athens, Georgia, 1986-1990. David Disney U.S. EPA Center for Exposure Assessment Modeling College Station Road Athens, GA 30613
FESWMS-2DH	Finite element surface water modeling system for two-dimensional flow in a horizontal plane. 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).	Developed for U.S. Geological Survey, Reston, VA Dr. David Froehlich Department of Civil Engineering University of Kentucky Lexington, KY
TPA	Tidal Prism Analysis.	U.S. EPA. 1985. *Coastal Marinas Assessment Handbook*. U.S. EPA, Region 4, Atlanta, GA.
CE-QUAL-W2	Consists of directly coupled hydrodynamic and water quality transport models. Can simulate suspended solids and accumulation and decomposition of detritus and organic sediment. Two-dimensional in the x-z plane.	Developed by U.S. Army Corps of Engineers Waterways Experiment Station in 1986. U.S. Army Waterways Experiment Station Hydraulics Laboratory P.O. Box 631 Vicksburg, MS 39180-0631

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; and
(6) Demonstrated applicability to size and type of project.

The Center for Exposure Assessment Modeling (CEAM), EPA Environmental Research Laboratory, Athens, Georgia, provides continual support for several hydrodynamic and surface water quality models. Another source of information and technical support is the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi. 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 from 1 to 12 person-months (Table 6-2).

Model Limitations

Factors that need to be considered in the application of mathematical models to predict impacts from hydromodification projects include:

- Variations in the accuracy of these models when they are applied to the short- and long-term response of natural systems;
- The availability of relevant information to derive the simulations and validate the modeling results;
- The substantial computer time required for long-term simulations of 3D hydrodynamic and surface water quality process models; and
- The need for access to sophisticated equipment such as the CRAY-XMP.

▨ *b. Identify and evaluate appropriate BMPs for use in the design of proposed channelization or channel modification projects or in the operation and maintenance program of existing projects. Identify and evaluate positive and negative impacts of selected BMPs and include costs.*

Several available surface water 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.

Table 6-2. Approximate Levels of Effort for Hydrodynamic and Surface Water Quality Modeling

Dimensionality	Surface Water Quality Parameter	Approximate Level of Effort
1D steady state	DO, BOD, nutrient	1-2 person-months
1D, 2D steady state	DO, BOD, nutrient, phytoplankton, toxics	1-4 person-months
1D, 3D time-variable	DO, BOD, nutrient, phytoplankton, toxics	1-12 person-months

Streambank Protection

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;
- Regulation of irrigation near streambanks and rerouting of overbank drainage; and
- Minimization of loads on top of streambanks (such as prevention of building within a defined distance from the streambed).

Several structural practices are used in the protection or the rehabilitation of 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). Indirect bank protection requires less bank grading and tree and snag removal.

Direct methods for streambank protection include stone riprap revetment, erosion control fabrics and mats, revegetation, burlap sacks, cellular concrete blocks, and bulkheads. Indirect methods include dikes, wire or board fences, gabions, and stone longitudinal dikes. The feasibility of these practices depends on the engineering design of the structure, the availability of the protecting material, the 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, would further reduce the engineering and maintenance efforts.

Innovative designs of streambank protection tailored to specific environmental goals and site conditions may result in beneficial effects. Several innovative channel profiling and revetment design considerations were reviewed by Henderson and Shields (1984), including composite revetments for deep channels with flow concentrated along the bank line, windrow revetments for actively eroding and irregular banks, and reinforced revetments (stone toe protection) to control underwater activities adjacent to high banks. Composite revetments placed along the Missouri River were built with a combination of stone, gravel, clay, and flood-tolerant vegetation to protect the streambank (USACE, 1981). The different materials were selected to match the erosive potential of the streambank zones. Beneficial environmental impacts that can be achieved by this type of design include higher densities and abundance of riparian vegetation on the top bank, allowing flood-tolerant species to colonize the clay and gravel of the splash zone. The design was reported to provide better access to the channel by wildlife, and it had a greater aesthetic value.

An excavated bench (compound channel) streambank protection design, based on streambed stabilization, was used to control erosion activities on the Yazoo River tributaries in Mississippi. These tributaries were experiencing extensive bed degradation and channel migration. The design consisted of structural protection to the water elevation reached during 90 to 95 percent of the annual storm events, a flattened bench excavated just above the structural protection to provide a suitable growing environment for wood vegetation and shrubs, and a grass-seeded upper bank, which could be succeeded by native species. This practice has been reported to be successful in controlling streambank erosion (Bowie, 1981).

Streambank protection structures may impact the riparian wildlife community if the stabilization effort alters the quality of the riparian habitat. 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.

Levee Protection

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.

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 (Hynson et al., 1985). Additionally, a balance between the vegetation management practices for instream and riparian habitat and engineering considerations should be maintained to avoid structural compromise (Hynson et al., 1985). 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 (Hynson et al., 1985). Recreational area management includes upkeep of planted areas, disposal of solid waste, and repairing of facilities (Hynson et al., 1985).

Channel Stabilization and Flow Restrictors

Channel stabilization using 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 boulders; and
- Control the direction of flow and the position of the stream.

Check Dam Systems

The Los Angeles River Watershed (1973) evaluated the cost-effectiveness of check dam systems as sediment control structures in the Angeles National Forest. In general, the check dam systems were found to be marginally cost-effective and were able to provide some beneficial sediment-reduction functions.

Swanson and others (1987) described the use of 71 check dams in the headwaters area of a perennial stream in northwestern Nevada. Watershed management problems, such as a history of overgrazing, led to riparian habitat degradation in streamside areas and severe gullying. The problem was ameliorated with changes in watershed management practices (livestock exclusion in streamside areas or limited grazing programs) and structural practices (check dams). Loose rock check dams, designed for 25-year floods, were selected for their ability to retard water velocities and trap sediment.

Benefits of this planned channel modification project include both instream and streamside changes. Sediment was trapped behind the dams (average of 0.9 foot in 2 years), and small wetland areas were established behind most dams. Additionally, over one-half of the channel length was vegetated in the deepest areas and the entire channel was at least partially vegetated. Streamside benefits included increased bird and plant diversity and abundance.

Grade Control Structures - Streambank and Channel Stabilization

Grade control structures (GCS) are hydraulic barriers (weirs) installed across streams to stabilize the channel, control headcuts and scour holes, and prevent upstream degradation. These structures can be built with a variety of materials, including sheet piling, stone, gabions, or concrete. Grade control structures are usually installed in combination with other practices to protect streambanks and direct the stream flow. Grade control structure design needs to account for stream morphologic, hydrologic, and hydraulic characteristics to determine the range of stream discharges for which the structure will function. Additionally, the upstream distance influenced by the structure, changes to surface water profiles, and the sediment transport capacity of the targeted stream reach need to be considered.

Shields and others (1990) evaluated the efficiency of GCS installed on Twentymile Creek (northeast Mississippi) to address channel instability. Effects on bank line vegetation were assessed using a before-and-after approach. Benefits of the GCS included local channel aggradation for about 1 mile upstream of each structure, increased streambank vegetation, locally increased fish species diversity downstream from the GCS, and the creation of low-flow velocities and greater pool depths downstream from the GCS. The primary problem associated with the project was the continued general streambed degradation after the structures were installed.

Vegetative Cover

Streambank protection using vegetation is probably the most commonly used practice, particularly in small tributaries. Vegetative cover, also used in combination with other structural practices, is relatively easy to establish and maintain, is visually attractive, and is the only streambank stabilization method that can repair itself when damaged (USACE, 1983). Appropriate native plant species should be used. Vegetation growing under the waterline 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.

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.

Instream Sediment Load Control

Instream sediment can be controlled by using several structural 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. 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).

Noneroding Roadways

Farm, forestry, and other 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. 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; and 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. Chapter 3 of this document reviews available practices for rural road construction and management to minimize impacts on waterbodies in coastal zones. Chapter 4 outlines practices and design concepts for construction and management of roads designed for heavier traffic loads and can be applied to planning and installation of roads and highways in coastal areas.

Setback Levees and Flood Walls

Levees and flood walls are longitudinal structures used to reduce flooding and minimize sedimentation problems associated with fluvial systems. They can be constructed without disturbing the natural channel vegetation, cross section, or bottom slope. Usually no immediate instream effects from sedimentation are caused by implementing this type of modification. However, there may be a long-term problem in channel adjustment (USACE, 1989).

Siting of levees and flood walls 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.

5. Costs for Modeling Practices

Costs for modeling of channelization and channel modification activities range from $1,500 to over $5,000,000 (see Table 6-3). Generally, more expensive modeling requires custom programming, extensive data collection, detailed calibration and verification, and larger computers. The benefits of more expensive modeling include a more detailed analysis of the problem and the ability to include more variables in the model. Less expensive models, in general, have minimal data requirements and require little or no programming, and they can usually be run on smaller computers. The difference in cost roughly corresponds to the detail that can be expected in the final analysis.

Table 6-3. Costs of Models for Various Applications

Application	Model	Cost ($)
Channel Maintenance	Physical model of estuary, river, or stream "from scratch"	500,000 to 5,000,000
	Existing physical model of estuary, river, or stream	50,000 to 500,000
	3D hydrodynamic and salinity model	50,000 to 200,000
	TABS-2 application for sedimentation	50,000 to 200,000
	TPA application to a marina basin	1,500 to 3,000
	WASP4 application to a marina basin	15,000 to 50,000
Dams and Impoundments	WASP4 application to an estuary or a reservoir	50,000 to 150,000
	CE-QUAL-W2 application to an estuary or a reservoir	50,000 to 100,000
	Estuarine or reservoir sediment transport models	unlimited
Tidal Flow Restrictors	FESWMS-2DH application of tidal flow restriction	15,000 to 30,000
	WASP4 application of tidal flow restriction	50,000 to 150,000
Flow Regime Alterations	WASP4 application of flow regime alteration	50,000 to 150,000
Breakwaters and Wave Barriers	CAFE finite element circulation model	15,000 to 50,000
	EFDC finite difference 3D model	20,000 to 60,000
	WASP4 application to harbor system	15,000 to 50,000
Excavation of Uplands for Marina Basins or Lagoon Systems	CAFE/DISPER models	15,000 to 50,000
	EFDC 3D hydrodynamic model	20,000 to 60,000
	WASP4 application to marina/lagoon	15,000 to 50,000

B. Instream and Riparian Habitat Restoration Management Measure

(1) Evaluate the potential effects of proposed channelization and channel modification on instream and riparian habitat in coastal areas;

(2) Plan and design channelization and channel modification to reduce undesirable impacts; and

(3) Develop an operation and maintenance program with specific timetables for existing modified channels that includes identification of opportunities to restore instream and riparian habitat in those channels.

1. Applicability

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. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with management measures and will have some flexibility in doing so. The application of this management measure by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

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 is intended to occur concurrently with the implementation of Management Measure A (Physical and Chemical Characteristics of Surface Waters) of this section.

Contact between floodwaters and overbank soil and vegetation can be increased by a combination of setback levees and use of compound-channel designs. Levees set back away from the streambank (setback levees) can be constructed to allow for overbank flooding, which provides surface water contact to important streamside areas (including wetlands and riparian areas). Additionally, setback levees still function to protect adjacent property from flood damage. Compound-channel designs consist of an incised, narrow channel to carry surface water during low (base)-flow periods, a staged overbank area into which the flow can expand during design flow events, and an extended overbank area, sometimes with meanders, for high-flow events. Planting of the extended overbank with suitable vegetation completes the design.

Preservation of ecosystem benefits can be achieved by site-specific design to obtain predefined optimum or existing ranges of physical environmental conditions. Mathematical models can be used to assist in site-specific design.

Instream and riparian habitat alterations caused by secondary effects can be evaluated by the use of models and other decision aids in the design process of a channelization and channel modification activity. After using models to evaluate secondary effects, restoration programs can be established.

3. Management Measure Selection

Selection of this management measure was based on the following factors:

(1) Published case studies that show that channelization projects cause instream and riparian habitat degradation. For example, wetland drainage due to hydraulic modifications was found to be significant by several researchers (Barclay, 1980; Erickson et al., 1979; Schoof, 1980; Wilcock and Essery, 1991).

(2) Published case studies that note instream habitat changes caused by channelization and channel modifications (Reiser et al., 1985; Sandheinrich and Atchison, 1986).

4. Practices

As explained more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require implementation of practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

▨ *a. 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.*

Expert Judgment and Check Lists

Approaches using expert judgment and check lists developed based on experience acquired in previous projects and case studies may be very helpful in integrating environmental goals into project development. This concept of incorporating environmental goals into project design was used by the U.S. Army Corps of Engineers (Shields and Schaefer, 1990) in the development of a computer-based system for the environmental design of waterways (ENDOW). The 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.

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.

Habitat Evaluation Procedures

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:

(1) The relative value of different areas at the same point in time and
(2) 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 (USDOI-FWS, 1980).

Rapid Bioassessment Protocols - Habitat Assessment

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). 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. The procedure typically can be performed by a field crew of one person in approximately 20 minutes per sampling site.

Rapid Bioassessment Protocol III - Benthic Macroinvertebrates

Rapid Bioassessment Protocols (Plafkin et al., 1989) 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.

Rosgen Stream Classification System - Fish Habitat

Rosgen (1985) has developed a stream classification system that categorizes various stream types by morphological characteristics. Based on characteristics such as gradient, sinuosity, width/depth ratio, bed particle size, channel entrenchment/valley confinement, and landform features and watershed soil types, stream segments can be placed within major categories. Subcategories can be delineated using additional factors including organic debris, riparian vegetation, stream size, flow regimen, depositional features, and meander patterns. The method is designed to be applied using aerial photographs and topographic maps, with field validation necessary for gradients, particle size, and width/depth ratios. Rosgen and Fittante (1986) have prepared guidelines for fish habitat improvement structure suitability based on Rosgen's (1985) classification system. The methods have been used in the western States and have had some application in the eastern States.

Simon and Hupp Channel Response Model - Stream Habitat

A conceptual model of channel evolution in response to channelization 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 empirically 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.

Temperature Predictions

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, and (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. An instream surface water temperature model was developed by the U.S. Fish and Wildlife Service (Theurer et al., 1984) to predict mean daily temperature and diurnal fluctuations in surface water temperatures throughout a stream system. The model 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.

Index of Biological Integrity - Fish Habitat

Karr et al. (1986) describe an Index of Biological Integrity (IBI), which includes 12 matrices 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 over two dozen States across the country to assess a wide range of impacts in streams and rivers.

Simon and Hupp Vegetative Recovery Model - Streamside Habitat

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).

▨ b. *Identify and evaluate appropriate BMPs for use in the design of proposed channelization or channel modification projects or in the operation and maintenance program of existing projects. Identify and evaluate positive and negative impacts of selected BMPs and include costs.*

Operation and maintenance programs should include provisions to use one or more of the approaches described under Practice "b" of Management Measure A of this section. 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 in an operation and maintenance program:

- Streambed protection;
- Levee protection;
- Channel stabilization and flow restrictors;
- Check dams;
- Vegetative cover;
- Instream sediment load control;
- Noneroding roadways; and
- Setback levees and flood walls.

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.

III. DAMS MANAGEMENT MEASURES

The second category of sources for which management measures and practices are presented in this chapter is dams. Dams are defined as constructed impoundments that are either (1) 25 feet or more in height *and* greater than 15 acre-feet in capacity, or (2) 6 feet or more in height *and* greater than 50 acre-feet in capacity.[1]

Based on this definition, there are 7,790 dams located in coastal counties of the United States, of which 6,928 dams are located in States with approved coastal zone programs (Quick and Richmond, 1992).

The siting and construction of a dam can be undertaken for many purposes, including flood control, power generation, irrigation, livestock watering, fish farming, navigation, and municipal water supply. Some reservoir impoundments are also used for recreation and water sports, for fish and wildlife propagation, and for augmentation of low flows. Dams can adversely impact the hydraulic regime, the quality of the surface waters, and habitat in the stream or river where they are located. A variety of impacts can result from the siting, construction, and operation of these facilities.

Dams are divided into the following classes: run-of-the-river, mainstem, transitional, and storage. A run-of-the-river dam is usually a low dam, with small hydraulic head, limited storage area, short detention time, and no positive control over lake storage. The amount of water released from these dams depends on the amount of water entering the impoundment from upstream sources. Mainstem dams, which include run-of-the-river dams, are characterized by a retention time of approximately 25 days and a reservoir depth of approximately 50 to 100 feet. In mainstem dams, the outflow temperature is approximately equal to the inflow temperature plus the solar input, thus causing a "warming" effect. Transitional dams are characterized by a retention time of about 25 to 200 days and a maximum reservoir depth of between 100 and 200 feet. In transitional dams, the outflow temperature is approximately equal to the inflow temperature so that during the warmer months coldwater fish cannot survive unless the inflows are cold. The storage dam is typically a high dam with large hydraulic head, long detention time, and 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 feet. The outflow temperature is sufficient for coldwater fish, even with warm inflows.

The siting of dams can result in the inundation of wetlands, riparian areas, and fastland in upstream areas of the waterway. Dams either reduce or eliminate the downstream flooding needed by some wetlands and riparian areas. Dams can also impede or block migration routes of fish.

Construction activities from dams can cause increased turbidity and sedimentation in the waterway resulting from vegetation removal, soil disturbance, and soil rutting. Fuel and chemical spills and the cleaning of construction equipment (particularly concrete washout) have the potential for creating nonpoint source pollution. The proximity of dams to streambeds and floodplains increases the need for sensitivity to pollution prevention at the project site in planning and design, as well as during construction.

The operation of dams can also generate a variety of types of nonpoint source pollution in surface waters. Controlled releases from dams can change the timing and quantity of freshwater inputs into coastal waters. Dam operations may lead to reduced downstream flushing, which, in turn, may lead to increased loads of BOD, phosphorus, and nitrogen; changes in pH; and the potential for increased algal growth. Lower instream flows, and lower peak flows associated with controlled releases from dams, can result in sediment deposition in the channel several miles downstream of the dam. The tendency of dam releases to be clear water, or water without sediment, can result in erosion of the streambed and scouring of the channel below the dam, especially the smaller-sized sediments. One result is the siltation of gravel bars and riffle pool complexes, which are valuable spawning and nursery habitat for fish. Dams also limit downstream recruitment of suitably-sized substrate required for the anchoring and growth of aquatic plants.

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[1] This definition is consistent with the Federal definition at 33 CFR 222.8(h)(1) (1991).

Finally, reservoir releases can alter the water temperature and lower the dissolved oxygen levels in downstream portions of the waterway.

The extent of changes in downstream temperature and dissolved oxygen from reservoir releases depends on the retention time of water in the reservoir and the withdrawal depth of releases from the reservoir. Releases from mainstem projects are typically higher in dissolved oxygen than are releases from storage projects. Storage reservoir releases are usually colder than inflows, while releases from mainstem reservoirs depend on retention time and depth of releases. Reservoirs with short hydraulic residence times have reduced impacts on tailwaters (Walburg et al., 1981).

It is important to note that the operation of dams can have positive, as well as negative, effects on water quality, aquatic habitat, and fisheries within the pool and downstream (USEPA, 1989). Potential positive effects include:

- Creation of above-the-dam summer pool refuge during low flows, an effect that has been documented for small dams built in the upper stream reaches of the Willamette River in the northwest United States (Li et al., 1983);

- Creation of reservoir sport fisheries (USDOI, 1983); and

- Less scouring and erosion of streambanks as a result of reduced velocities in downstream areas.

Once a river is dammed and a reservoir is created, processes such as stratification, seasonal overturn, chemical cycling, and sedimentation can intensify to create several NPS pollution problems. These processes occur primarily as a result of the presence of the dam, not the operation of the dam.

Stratification is the layering of a lake into an upper, well-lighted, productive, and warm layer, called the *epilimnion*; a mid-depth transitional layer, the *metalimnion*; and a lower, dark, cold, and unproductive layer, the *hypolimnion*. These layers are separated by a thermocline in the metalimnion, a sharp transition in water temperature between upper warm water and lower cold water (Figure 6-1). This stratification varies seasonally, being most pronounced in the summer and absent in the winter. Between these extremes are periods of less pronounced stratification and spring and fall overturns, when the entire waterbody mixes together. Poor mixing conditions, resulting in stratification, are estimated to occur in 40 percent of power impoundments and 37 percent of non-power impoundments (USEPA, 1989).

Dissolved oxygen levels are tied to the overturn, mixing, and stratification processes. Dissolved oxygen concentration in reservoir waters is the result of a delicate balance between both oxygen-producing and oxygen-consuming processes (Bohac and Ruane, 1990). Dissolved oxygen tends to become depleted in the hypolimnion due to decomposition of organic substances, algal respiration, and nitrification. The epilimnion, however, tends to be enriched with oxygen from the atmosphere and as a product of photosynthesis. The net difference between oxygen consumption and oxygen sources can create anoxic conditions in the lower layer (Figure 6-2).

Anoxic conditions in the hypolimnion may stimulate the formation of reduced species of iron, manganese, sulfur, and nitrogen. Chemical cycling of these elements occurs when they change from one state to another (e.g., from solid to dissolved). Many chemicals enter a reservoir attached to sediment particles or quickly become attached to sediment. As a solid, many chemicals typically are not toxic to many organisms, especially those in the water column. Some chemicals are easily reduced under anoxic conditions and become soluble. The reduced and soluble forms of many chemicals and compounds are toxic to most aquatic organisms at relatively low concentrations. For example, hydrogen sulfide is toxic to aquatic life and corrosive to construction materials at concentrations that are considerably lower than those detectable by commonly used procedures (Johnson et al., 1991). These reduced chemical compounds lead to taste and odor problems in drinking water supplies and toxicity problems for fish.

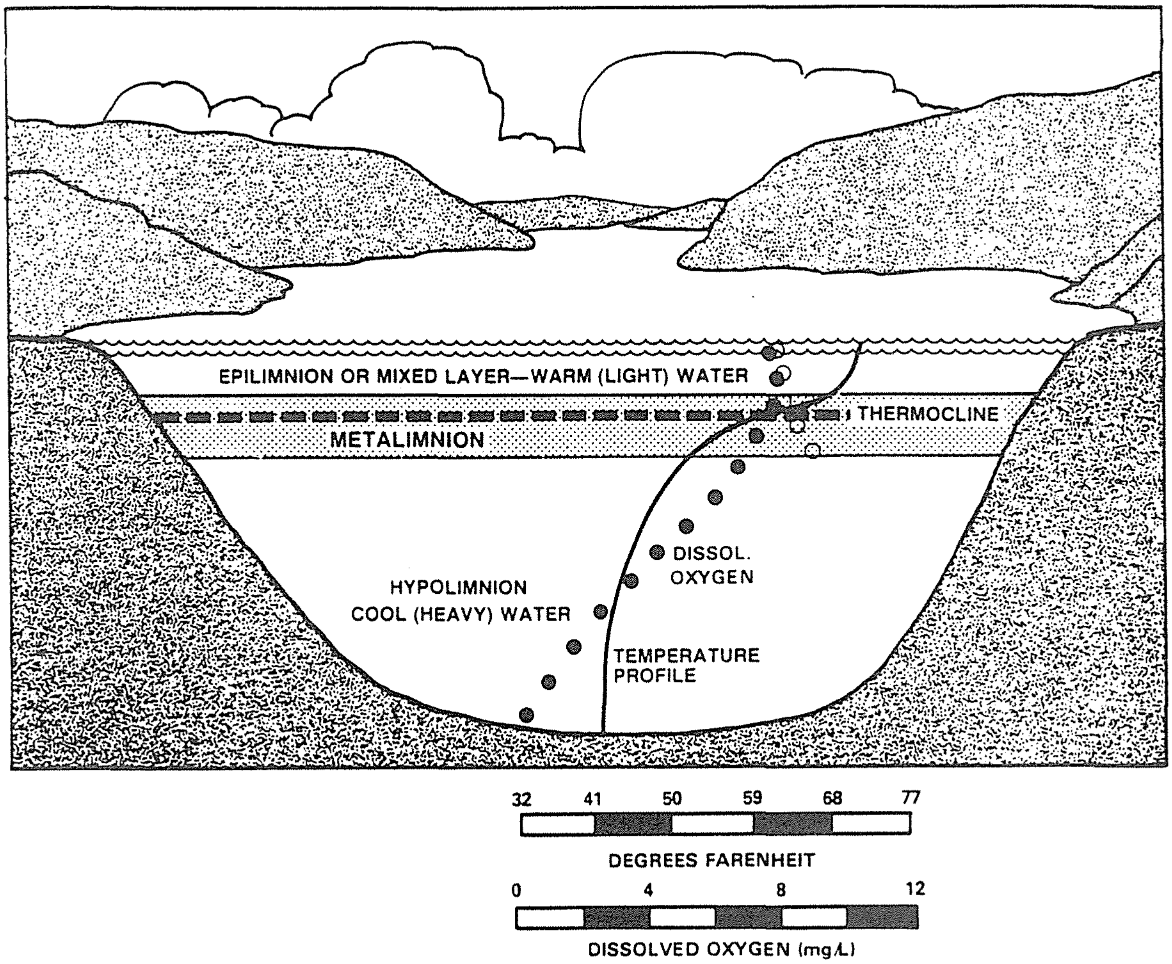

Figure 6-1. A cross-sectional view of a thermally stratified reservoir in mid-summer. The water temperature profile (curved solid line) illustrates how rapidly the water temperature decreases in the metalimnion compared to the nearly uniform temperatures in the epilimnion and hypolimnion. The solid circles represent the dissolved oxygen (DO) profile. The rate of organic matter decomposition is sufficient to deplete the DO content of the hypolimnion (USEPA, 1990).

Hydraulic residence time is defined as the average time required to completely renew a waterbody's water volume. For example, rivers have little or no hydraulic residence time, lakes with small volumes and high flow rates have short hydraulic residence times, and lakes with large volumes and low flow rates have long hydraulic residence times. Reservoirs differ from lakes in that, among other characteristics, their flow is regulated artificially. Hydraulic residence times of reservoirs are generally shorter than those of lakes, giving the water flowing into the reservoir less time to mix with the resident water.

The longer the hydraulic residence time, the greater the potential for incoming nutrients and sediment to settle in the reservoir. Conditions that lead to eutrophication in reservoirs promote increased algal growth, which in turn lead to a greater mass of dead plant cells. In reservoirs with long residence times, a major source of organic sediment settling to the bottom can be dead plant cells. Sediment will settle to the bottom; but, where reservoir releases are taken from the lower layer, they will release colder water downstream that is rich in nutrients, low in dissolved oxygen, and higher in some dissolved species such as iron, manganese, sulfur, and nitrogen.

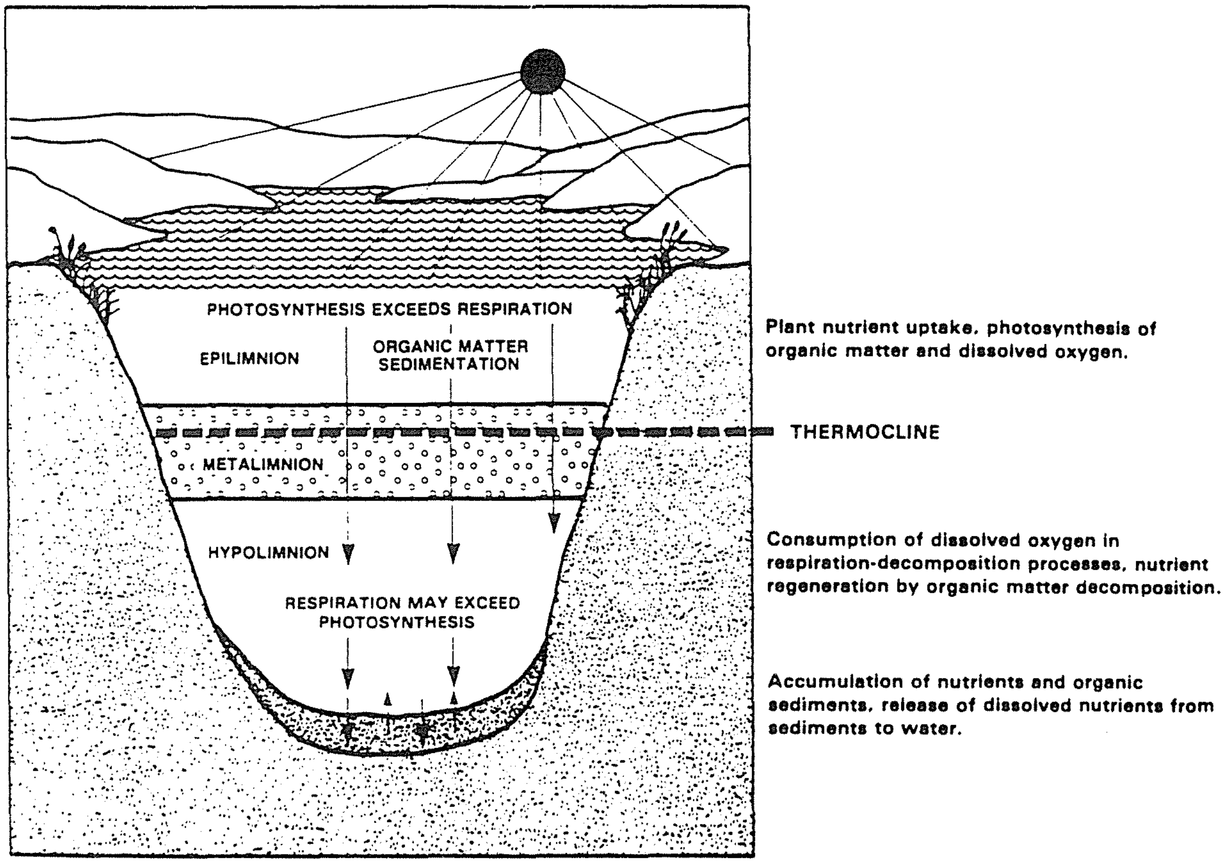

Figure 6-2. Influence of photosynthesis and respiration-decomposition processes and organic matter sedimentation on the distribution of nutrients and organic matter in a stratified reservoir (USEPA, 1990).

Management Measures A and B address two problems associated with the construction of dams:

(1) Increases in sediment delivery downstream resulting from construction and operation activities and
(2) Spillage of chemicals and other pollutants to the waterway during construction and operation.

The impacts of reservoir releases on the quality of surface waters and instream and riparian habitat in downstream areas is addressed in Management Measure III.C.

A. Management Measure for Erosion and Sediment Control

(1) Reduce erosion and, to the extent practicable, retain sediment onsite during and after construction, and

(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.

1. Applicability

This management measure is intended to be applied by States to the construction of new dams, as well as to construction activities associated with the maintenance of dams. Dams are defined[2] as constructed impoundments which are either:

(a) 25 feet or more in height *and* greater than 15 acre-feet in capacity, or
(b) six feet or more in height *and* greater than 50 acre-feet in capacity.

This measure also does not apply to projects that fall under NPDES jurisdiction. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with this measure and will have some flexibility in doing so. The application of management measures by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

The purpose of this management measure is to prevent sediment from entering surface waters during the construction or maintenance of dams. Coastal States should incorporate this measure into existing State erosion and sediment control (ESC) programs or, if such programs are lacking, should develop them. States should incorporate this measure into ESC programs at the local level also. Erosion and sediment control is intended to be part of a comprehensive land use or watershed management program. (Refer to the Watershed and Site Development Management Measures in Chapter 4.)

Runoff from construction sites is the largest source of sediment in urban areas (Maine Department of Environmental Protection, Bureau of Water Quality, and York County Soil and Water Conservation District, 1990). Eroded sediment from construction sites creates many problems in coastal areas including adverse impacts to water quality, critical instream and riparian habitats, submerged aquatic vegetation (SAV) beds, recreational activities, and navigation.

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[2] This definition is consistent with the Federal definition at 33 CFR 222.8(h)(1) (1991).

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 and provide for prevention of erosion and sediment problems and accountability if a problem occurs (Maine Department of Environmental Protection, 1990). Chapter 4 of this guidance presents a full description of construction-related erosion problems and the value of ESC plans. Readers should refer to Chapter 4 for further information.

3. Management Measure Selection

This management measure was selected because of the importance of minimizing sediment loss to surface waters during dam construction. 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.

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

4. Practices

As discussed more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require the implementation of these practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

Practices for the control of erosion and sediment loss are discussed in Chapter 4 of this guidance and should be considered applicable to this management measure. 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) stabilizing disturbed soils to prevent erosion. The following practices have been found to be useful in these purposes and should be incorporated into ESC plans and used during dam construction as appropriate.

Additional discussions of the practices described below can be found in Chapter 4 of this guidance and should be referred to for more information.

▨ a. *Preserve trees and other vegetation that already exist near the dam construction site.*

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 should 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.

▨ b. *Control runoff from the construction site and construction-related areas.*

The largest surface water pollution problem during construction is turbidity resulting from aggregate processing, excavation, and concrete work. Preventing the entry of these materials into surface waters is always the preferable alternative because runoff due to these activities can adversely affect drinking water supplies, irrigation systems, and river ecology (Peters, 1978). If onsite treatment is necessary, methods are available to control the runoff of sediment and wastewater from the construction site. Sedimentation in settling ponds, sometimes with the addition of chemical precipitating agents, is one such method (Peters, 1978). Flocculation, the forced coagulation of fine-grained sediment through agitation to settle particles out of solution, is another method. Chemical precipitating agents can also be used in this flocculation process (Peters, 1978). Filtration with sand, anthracite, diatomaceous earth, or finely woven material, used singly or in combination, may be more useful than other methods for coarser grained materials (Peters, 1978).

c. Control soil and surface water runoff during construction.

To prevent the entry of sediment used during construction into surface waters, the following 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; and identify measures to reduce runoff from such areas if disturbance of these areas cannot be avoided (Hynson et al., 1985). Refer to Chapter 4 for additional information.

Runoff control measures, mechanical sediment control measures, grassed filter strips, mulching, and/or sediment basins should 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. Refer to Chapter 4 for additional information.

d. Other practices

Many other practices for the control of erosion and sediment loss are discussed in Chapter 4 of this guidance, which should be referred to for a complete discussion where noted. Below are brief descriptions of some of the other practices.

- **Revegetation.** Revegetation of construction sites during and after construction is the most effective way to permanently control erosion (Hynson et al., 1985). Many erosion control techniques are also intended to expedite revegetation.

- **Mulching.** Various mulching techniques are used in erosion control, such as use of straw, wood chip, or stone mulches; use of mulch nets or blankets; and hydromulching (Hynson et al., 1985). Mulching is used primarily to reduce the impact of rainfall on bare soil, to retain soil moisture, to reduce runoff, and often to protect seeded slopes (Hynson et al., 1985).

- **Soil Bioengineering.** Soil bioengineering techniques can be used to address the erosion resulting from dam operation. Grading or terracing a problem stream bank or eroding area and using interwoven vegetation mats, installed alone or in combination with structural measures, will facilitate infiltration stability. Refer to the section on shore protection in this chapter for additional information.

5. Effectiveness for All Practices

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 system. 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. Chapter 4 has additional information for effectiveness of the practices listed above.

6. Costs for All Practices

Chapter 4 of this guidance contains the available cost data for most of the erosion controls listed above. Costs in Chapter 4 have been broken down into annual capital costs, annual maintenance costs, and total annual costs (including annualization of capital costs).

B. Management Measure for Chemical and Pollutant Control

(1) Limit application, generation, and migration of toxic substances;

(2) Ensure the proper storage and disposal of toxic materials; and,

(3) Apply nutrients at rates necessary to establish and maintain vegetation without causing significant nutrient runoff to surface waters.

1. Applicability

This management measure is intended to be applied by States to the construction of new dams, as well as to construction activities associated with the maintenance of dams. Dams are defined[3] as constructed impoundments which are either:

(a) 25 feet or more in height *and* greater than 15 acre-feet in capacity, or
(b) 6 feet or more in height *and* greater than 50 acre-feet in capacity.

This management measure addresses fuel and chemical spills associated with dam construction, as well as concrete washout and related construction activities. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with this measure and will have some flexibility in doing so. The application of management measures by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

The purpose of this management measure is to prevent downstream contamination from pollutants associated with dam construction activities.

Although suspended sediment is the major pollutant generated at a construction site (USEPA, 1973), other pollutants include:

- Pesticides - insecticides, fungicides, herbicides, rodenticides;
- Petrochemicals - oil, gasoline, lubricants, asphalt;
- Solid wastes - paper, wood, metal, rubber, plastic, roofing materials;

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[3] This definition is consistent with the Federal definition at 33 CFR 222.8(h)(1) (1991).

- Construction chemicals - acids, soil additives, concrete-curing compounds;
- Wastewater - aggregate wash water, herbicide wash water, concrete-curing water, core-drilling wastewater, or clean-up water from concrete mixers;
- Garbage;
- Cement;
- Lime;
- Sanitary wastes; and
- Fertilizers.

A complete discussion of these pollutants can be found in Chapter 4 of this guidance.

3. Management Measure Selection

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 (USEPA, 1973). Some metals (e.g., manganese, iron, and nickel) attach to sediment 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).

A number of factors that influence the pollution potential of construction chemicals have been identified (USEPA, 1973). These include:

- The nature of the construction activity;
- The physical characteristics of the construction site; and
- 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.

4. Practices

As explained more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require the implementation of these practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

Practices for the control of erosion and sediment loss are discussed in Chapter 4 of this guidance and should be considered applicable to this management measure.

▨ *a. Develop and implement a spill prevention and control plan. Agencies, contractors, and other commercial entities associated with the dam construction project that store, handle, or transport fuel, oil, or hazardous materials should have a spill response plan, especially if large quantities of oil or other polluting liquid materials are used.*

Spill procedure information should be posted, and persons trained in spill handling should be onsite or on call at all times. Materials for cleaning up spills should be kept onsite and easily available. Spills should be cleaned up immediately and the contaminated material properly disposed of. Spill control plan components should include (Peters, 1978):

- Stopping the source of the spill;
- Containing any liquid;
- Covering the spill with absorbent material such as kitty litter or sawdust, but do not use straw; and
- Disposing of the used absorbent properly.

▨ *b. Maintain and wash equipment and machinery in confined areas specifically designed to control runoff.*

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 discharged into sanitary sewers if solids are removed from the solution first. Small parts should be cleaned with degreasing solvents that can then be reused or recycled. Do not discharge or otherwise dispose of any solvents into sewers, or into surface waters.

Washout from concrete trucks should be disposed of into:

- 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 in a dumpster; or

- A location not subject to surface water runoff and more than 50 feet away from a receiving water.

Never dump washout directly into surface waters or into a drainage leading to surface waters.

▨ *c. Establish fuel and vehicle maintenance staging areas located away from surface waters and all drainages leading to surface waters, and design these areas to control runoff.*

▨ *d. 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.*

C. Management Measure for Protection of Surface Water Quality and Instream and Riparian Habitat

Develop and implement a program to manage the operation of dams in coastal areas that includes an assessment of:

(1) Surface water quality and instream and riparian habitat and potential for improvement and

(2) Significant nonpoint source pollution problems that result from excessive surface water withdrawals.

1. Applicability

This management measure is intended to be applied by States to dam operations that result in the loss of desirable surface water quality, and of desirable instream and riparian habitat. Dams are defined[4] as constructed impoundments which are either:

(a) 25 feet or more in height *and* greater than 15 acre-feet in capacity, or
(b) 6 feet or more in height *and* greater than 50 acre-feet in capacity.

This measure does not apply to projects that fall under NPDES jurisdiction. This measure also does not apply to the extent that its implementation under State law is precluded under *California* v. *Federal Energy Regulatory Commission*, 110 S. Ct. 2024 (1990) (addressing the supersedence of State instream flow requirements by Federal flow requirements set forth in FERC licenses for hydroelectric power plants under the Federal Power Act).

Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with this measure and will have some flexibility in doing so. The application of management measures by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

The purpose of this management measure is to 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. Impacts from the operation of dams to surface water quality and aquatic and riparian habitat should be assessed and the potential for improvement evaluated. Additionally, new upstream and downstream impacts to surface water quality and aquatic and riparian habitat caused by the implementation of practices should also be considered in the assessment. The overall program approach is to

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[4] This definition is consistent with the Federal definition at 33 CFR 222.8(h)(1) (1991).

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, the program should implement the most cost-effective operations to protect surface water quality and aquatic and riparian habitat and to improve the water quality and aquatic and riparian habitat where economically feasible.

A variety of approaches have been developed and tested for their effectiveness at improving or maintaining acceptable levels of dissolved oxygen, temperature, phosphorus, and other constituents in reservoirs and tailwaters.

One general method uses pumps, air diffusers, or air lifts to induce circulation and mixing of the oxygen-poor, but cold hypolimnion with the oxygen-rich, but warm epilimnion. The desired result is a more thermally uniform reservoir with increased dissolved oxygen (DO) in the hypolimnion. Reservoir mixing improves water quality both in the reservoir and in tailwaters and helps to maintain the temperatures required by warm-water fisheries.

Another approach to improving water quality in tailwaters is appropriate if trout fisheries are desired downstream. In this approach, air or oxygen is mixed with water passing through the turbines of hydropower dams to increase the concentration of DO. Air or oxygen can be selectively added to impoundment waters entering turbine intakes. Reservoir waters can also be aerated by venting turbines to the atmosphere or by injecting compressed air into the turbine chamber.

A third group of approaches include engineering modifications to the intakes, the spillway, or the tailrace, or the installation of various types of weirs downstream of the dam to improve temperature or DO levels in tailwaters. These practices rely on agitation and turbulence to mix the reservoir releases with atmospheric air in order to increase the concentrations of dissolved oxygen. Selective withdrawal of water from different depths allows dam operators to maintain desired temperatures for fish and other aquatic species in downstream surface waters.

The quality of reservoir releases can also be improved through adjustments in the operational procedures at dams. These include scheduling releases or the duration of shutoff periods, instituting procedures for the maintenance of minimum flows, and making seasonal adjustments in the pool levels and in the timing and variation of the rate of drawdown.

Dam operators such as the Tennessee Valley Authority (TVA) further recognize the need for watershed management as a valuable tool to reduce water quality problems in reservoirs and dam releases. Reducing NPS pollutants coming from watersheds surrounding reservoirs can have a beneficial effect on concentrations of DO and pollutants within a reservoir and its tailwaters.

There is also a need for riparian habitat maintenance and restoration in the areas around the impounded reservoir and downstream from a dam. Reservoir shorelines are important riparian areas, and they need to be managed or restored to realize their many riparian habitat and water quality benefits. Examples of downstream aquatic habitat improvements include maintaining minimum instream flows, providing scouring flows when and where needed, providing alternative spawning areas or fish passage, protecting streambanks from erosion, and maintaining wetlands and riparian areas.

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 best management practice (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 raise water quality in the impoundment or in tailwaters to acceptable levels.

One such combination of practices has addressed low DO levels at the Canyon Dam (Guadalupe River, Texas). A combination of turbine venting and a downstream weir was used to increase DO levels to acceptable levels. The concentration of dissolved oxygen 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. The concentration of the same water after passing through the aeration weir was 6.7 mg/L (EPRI, 1990).

Another combination of practices, consisting of a vacuum breaker turbine venting system and a stream flow reregulation weir, has been implemented at Norris Dam (Clinch River, Tennessee). The vacuum breaker aeration system uses hub baffles and appears to be the most successful design (EPRI, 1990). The baffles induce enough air to add from 2 mg/L to 4 mg/L 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 (TVA, 1988).

Combinations of increased flow, stream aeration, and wasteload reduction (from municipal and industrial sources) were found to be necessary to treat releases from the Fort Patrick Henry Dam (Holston River, Tennessee). An unsteady state flow and water quality model was used to simulate concentrations of dissolved oxygen in the 20-mile downstream reach from Fort Patrick Henry Dam and to explore water quality management alternatives. Several pollution abatement options were considered to identify the most cost-effective alternative. These options included changing wasteloads of the various dischargers, varying the flows from the reservoir, and improving aeration levels in water leaving the reservoir and in areas downstream. The modeling study identified flow regime modifications as more effective in improving DO than wasteload modifications. However, a decision to increase flow from the dam when stream levels are low might result in unacceptable reservoir drawdown in dry years. Although at some projects the increased DO will persist for many miles, improvements that were predicted by aeration of dam releases diminished rapidly at this particular site because they decreased the DO deficit and reduced natural reaeration rates. No wasteload treatments short of total recycle would achieve the 5-mg/L standard under base conditions (Hauser and Ruane, 1985).

3. Management Measure Selection

Selection of this management measure was based on:

(1) The availability and demonstrated effectiveness of practices to improve water quality in impoundments and in tailwaters of dams and

(2) 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 dissolved oxygen levels in the impoundment and to decrease levels of other types of nonpoint source pollutants, such as manganese, iron, hydrogen sulfide, methane, ammonia, and phosphorus in reservoir releases (Cooke and Kennedy, 1989; Henderson and Shields, 1984);

- 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 (Hauser and Ruane, 1985; Henderson and Shields, 1984);

- Providing both minimum flows to enhance the establishment of desirable instream habitat and scouring flows as necessary to maintain instream habitat (Kondolf et al., 1987; Walburg et al., 1981);

- Establishing adequate fish passage or alternative spawning ground and instream habitat for fish species (Andrews, 1988); and
- 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 (Kortmann, 1989).

4. Introduction to Practices

As discussed more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require the implementation of these practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

5. Practices for Aeration of Reservoir Waters and Releases

The systems that have been developed and tested for reservoir aeration rely on atmospheric air, compressed air, or liquid oxygen to increase concentrations of dissolved oxygen in reservoir waters before they pass through the dam. Depending on the method selected, aeration can accomplish thorough mixing throughout the impoundment. However, this practice has not been used at large hydropower reservoirs because of the cost associated with aerating these large-flow reservoirs. Aeration will elevate levels of DO, but also will usually redistribute higher concentrations of algae found in the shallower depths and nutrients that are normally restricted to the deeper waters. It is not always desirable to have waters containing higher levels of algae and nutrients released into portions of the waterway below the dam (Kortmann, 1989). 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.

▨ a. *Pumping and Injection Practices*

One method for deployment of circulation pumps 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 (Cooke and Kennedy, 1989).

Air injection systems operate in a manner similar to that of pumping systems to mix water from different strata in the impoundment, except that air or pure oxygen is injected into the pumping system (Henderson and Shields, 1984). These kinds of systems are divided into two categories: 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 (Figure 6-3). The full air lift design has a higher efficiency than the partial-air lift and has a lesser tendency to elevate dissolved nitrogen levels (Cooke and Kennedy, 1989).

Diffused air systems provide effective transfer of oxygen to water by forcing compressed air through small pores in systems of diffusers to form bubbles (Figure 6-4). One test of a diffuser system 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

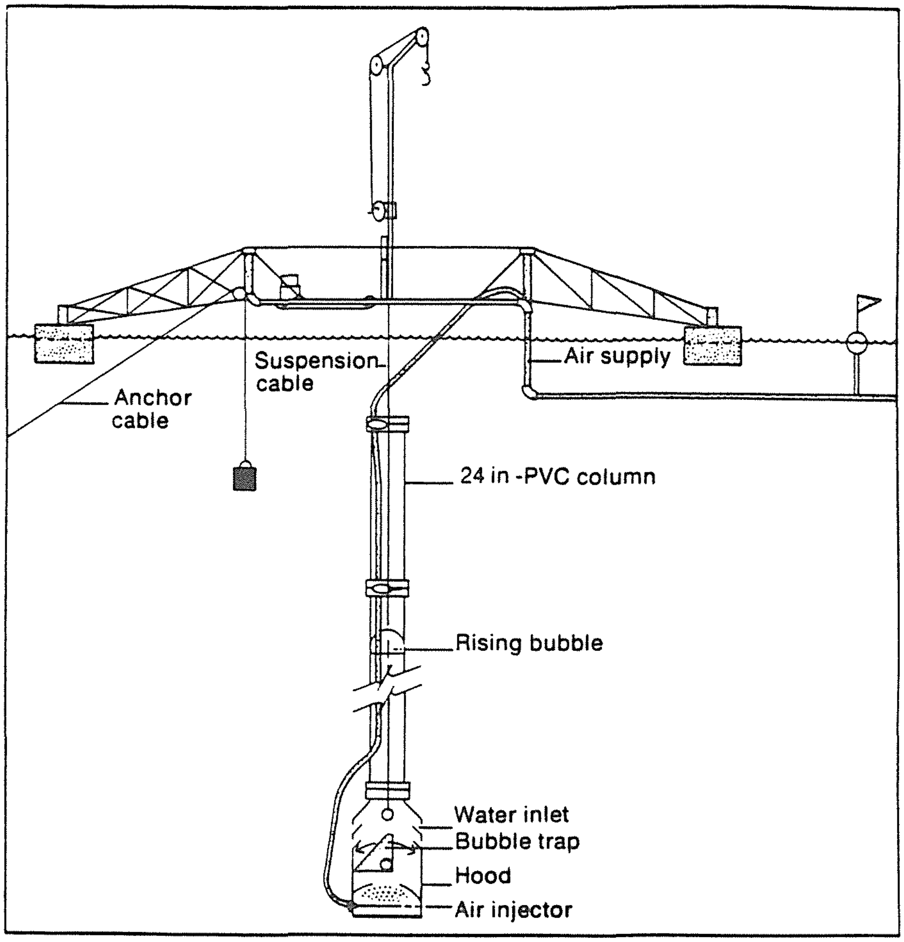


Figure 6-3. Air injection system for reservoir aeration-destratification (Nelson et al., 1978).

rate is rather low. But the results of this particular 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).

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).

Localized mixing is a practice to improve releases of 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).

Water pumps have been used to move surface water containing higher concentrations of DO downward to mix with deeper waters as the two strata are entering the turbine. Aspirating surface aerators deployed in Lake Texoma

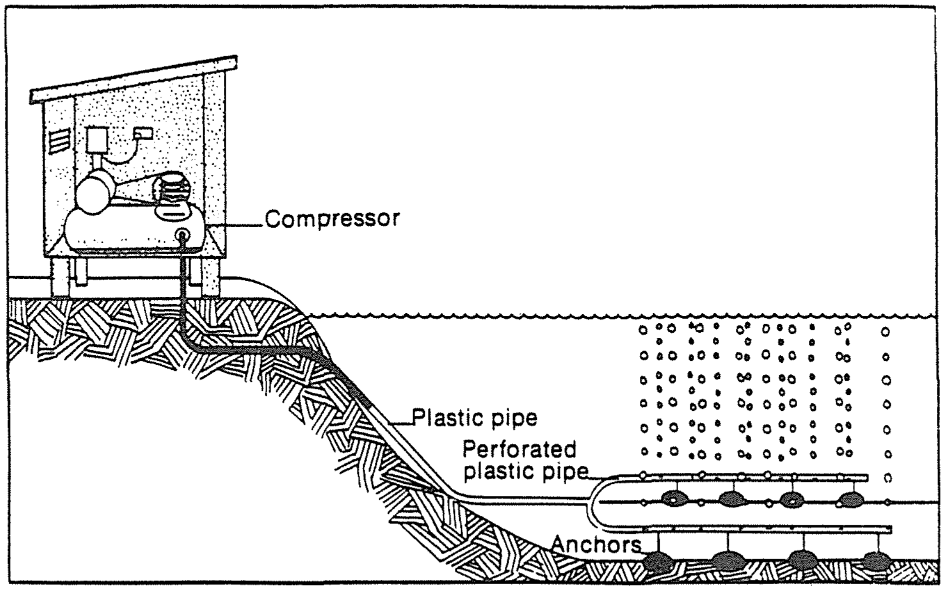


Figure 6-4. Compressed air diffusion system for reservoir aeration-destratification (Nelson et al., 1978).

(Texas/Oklahoma border) raised the levels of DO in the tailwaters from concentrations of 1.8 mg/L (without aerators) to 2.0 mg/L (with one 5-hp aeration unit in operation) and to 2.6 mg/L (with three 5-hp units operating).

A test of large-diameter axial-flow surface water pumps at Bagnell Dam (Lake of the Ozarks, Missouri) increased DO levels in the reservoir releases from 1.3 mg/L to 3.6 mg/L, before maintenance problems caused a discontinuance of use of the pumps (EPRI, 1990).

Small-diameter surface pumps, operated at the J. Percy Priest Dam (Tennessee), increased the DO levels in the tailwaters to 4.0 mg/L from a background level of 2.7 mg/L (EPRI, 1990).

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. Another type of 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).

The TVA has been testing the use of pure oxygen at the Douglas Dam (French Broad River, Tennessee) since 1988 (TVA, 1988). The absorption efficiencies measured in the downstream tailwaters range from 30 to 50 percent when the diffusers are arranged in a loose arc around the intakes. When the diffusers are placed tightly around the intakes, the efficiency range improves to 72 to 76 percent.

In another test at facilities operated by the Tennessee Valley Authority, diffusers were deployed to inject high-purity oxygen near the bottom of the 70-foot-deep reservoir at Fort Patrick Henry Dam (Holston River, Tennessee) near one of the turbine intakes. Levels of DO in the tailwaters increased from near 0 mg/L to 4 mg/L as a result of operation of this aeration system. Unfortunately, the operation costs of this kind of system were determined to be relatively high (Harshbarger, 1987). However, these results were very site-specific and every site needs to be evaluated for the best mix of solutions.

▨ b. 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 makes use of 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 (Figure 6-5). 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 to further improve the DO levels in the turbine releases (Jones and March, 1991).

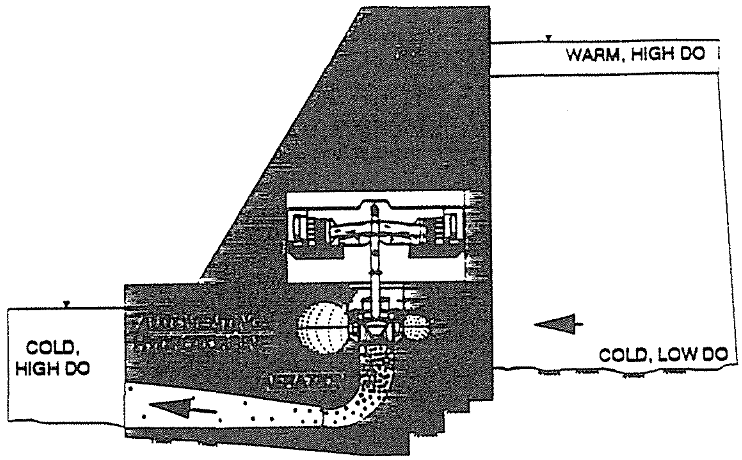
Recent developments in autoventing turbine technology show that it may be possible to aspirate air with no resulting decrease in turbine efficiency. In one test of an autoventing turbine at the Norris Dam (Clinch River, Tennessee), the turbine efficiency increased by 1.8 percent (March et al., 1991; Waldrop, 1992). Technologies like autoventing turbines are very site-specific and outcomes will vary considerably. Achievement of desired DO levels at specific projects may require evaluation of several different technologies.

6. Practices to Improve Oxygen Levels in Tailwaters

In addition to the pumping and injection systems for reservoir aeration discussed in the preceding section, another set of systems can accomplish the aeration of water as it passes through the dam or through the portion of the waterway immediately downstream from the dam. The systems in this category rely on agitation and turbulence to mix the reservoir releases with atmospheric air in order to increase the concentrations of dissolved oxygen. Another approach involves the increased use of spillways, which release surface water to prevent it from overtopping the dam. The third approach is to install barriers called weirs in the downstream areas. Weirs designed to allow water to overtop them can increase DO through surface agitation and increased surface area contact. Some systems create supersaturation of dissolved gases and may require additional modifications to prevent supersaturation.

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).



Concept of Autoventing Hydroturbine

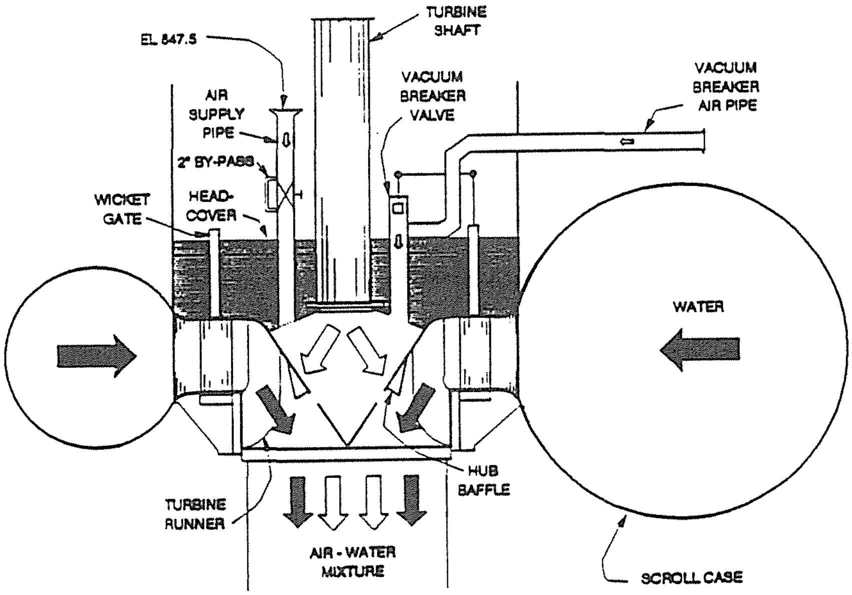


Figure 6-5. Top: Schematic drawing of an autoventing turbine. Bottom: Sketch of the hub baffle system used in the autoventing turbines at Norris Dam (French Broad River), Tennessee.(TVA-Engineering Laboratory, 1991.)

a. *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 the rest of the 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). In modeling studies, gated conduit structures have been found to achieve 90 percent aeration and a minimum DO standard of 5 mg/L (Wilhelms and Smith, 1981).

▨ b. Spillways

The U.S. Army Corps of Engineers has studied the performance of spillways and overflow weirs at its facilities to determine the importance of these structures in improving DO levels. Increases in DO concentration of about 2.5 mg/L have been measured at the overflow weir of the Jonesville Lock and Dam (Ouachita River, Louisiana) (Wilhelms, 1988). Increases in DO concentrations of 3 mg/L have been measured at the overflow weir of the Columbia Lock and Dam (Ouachita River, Louisiana). 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 (Wilhelms, 1988).

▨ c. Spillway Modifications

At the Tellico Dam (Little Tennessee River, Tennessee), a siphon/underwater barrier dam was installed to improve DO and temperature conditions in the releases. The installed siphon draws about 8 cfs of cool water from the reservoir over the spillway into the Little Tennessee River. During the summer, the water forms a pool behind a 6-ft high underwater barrier dam and creates the temperature and oxygen concentrations needed by striped bass. The fish attracted to the pool provide a desirable sport fishery for the community (TVA, 1988).

The operation of some types of hydraulic structures has been tied to problems stemming from the supersaturation of some types of gases. 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 saturation was 143 percent. In this case, the spillway was modified by cutting a notch to prevent water from plunging directly into the stilling basin (ASCE, 1986). At dams along the Columbia and Snake Rivers of the western United States, spillway deflectors have been found to be the most effective means for reducing nitrogen supersaturation (Bonneville Power Administration, 1991). The deflectors are designed to direct flows horizontally into the stilling basin to prevent deep plunging and air entrainment (ASCE, 1986).

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. The Columbia River of Washington State has a series of 11 dams beginning with the Grand Coulee and ending with Bonneville. The Snake River also has four dams. If all of these dams were spilling simultaneously, the entire river would become and remain highly saturated with nitrogen gas since the water would pick up gas at each successive spilling project. The Corps of Engineers 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 (Figure 6-6), 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).

▨ d. 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 U.S. Army Corps of Engineers 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. Although additional field tests are planned, current results indicate that overflow weirs aerate releases more effectively than low-sill spillways (Wilhelms, 1988).

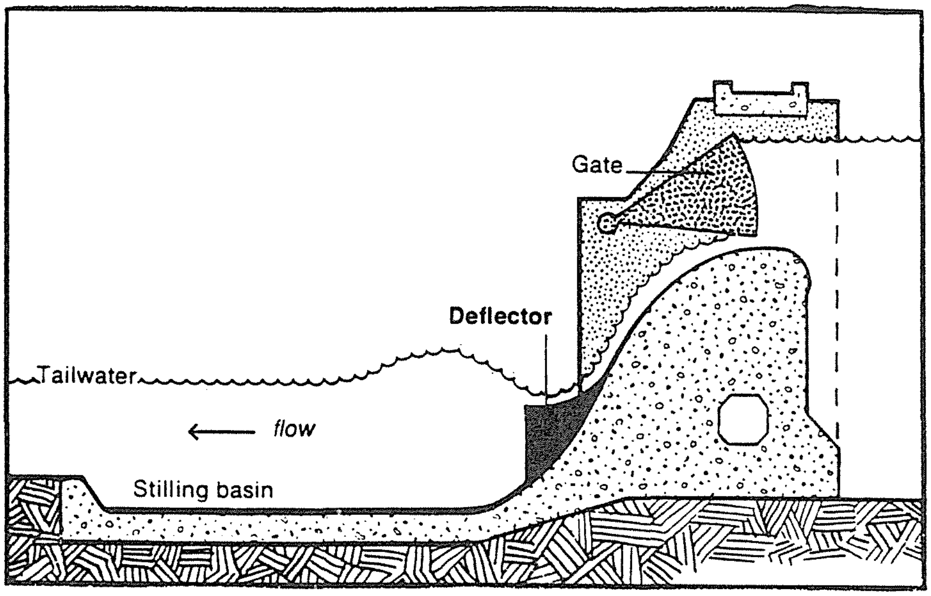


Figure 6-6. Cross section of a spillway with a "flip-lip" deflector (Nelson et al., 1978).

e. *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 (Figure 6-7) 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.

7. Practices for Adjustments in the Operational Procedures of Dams for Improvement of Water Quality

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 timed and scheduled so that the salinity regime in coastal waters is not substantially altered from historical patterns.

a. *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).

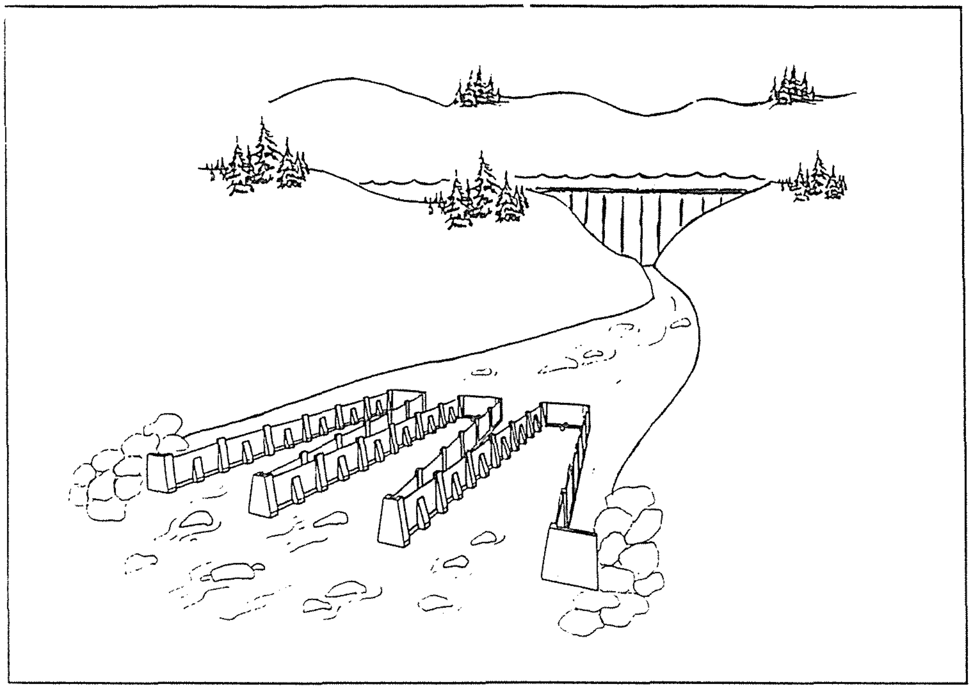


Figure 6-7. Three-bay labyrinth weir (Hauser et al., 1990).

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).

▨ b. *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 could be reduced by starting up all the generator units within a minute of each other (Findley and Day, 1987).

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 Corps of Engineers facilities to evaluate the downstream impacts on DO and temperature that would result from changes in several operational procedures, including (Hauser et al., 1990a, 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; and
- Timing and variation of the rate of drawdown.

8. Watershed Protection Practices

Most 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). Practices for watershed management include land use planning, erosion control, ground-water protection, mine reclamation, NPS screening and identification, animal waste control, and failing septic tank control (TVA, 1988).

Another general watershed management practice involves the evaluation of the total watershed and the use of point/nonpoint source trading. Simply put, this practice involves the evaluation of the sources of pollution in a watershed and determination of the most cost-effective combination of practices to reduce pollution among the various point and nonpoint sources. Podar and others (1985) present an excellent example of point/nonpoint source trading as applied to the Holston River near Kingsport, Tennessee. Bender and others (1991) used modeling to evaluate the cost-effectiveness of various point/nonpoint source trading strategies for the Boone Reservoir in the upper Tennessee River Valley.

a. 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). The watershed planning section of Chapter 4 contains additional information on land use planning.

b. Nonpoint Source Screening and Identification

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). TVA has used this technique 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).

c. 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). Chapter 4 in this guidance contains an extensive selection of practices aimed at preventing soil erosion and controlling sediment from reaching surface waters in runoff.

d. Ground-Water Protection

Proper protection and management of ground-water resources primarily depends on the effective control of NPS pollution, particularly in ground-water recharge areas. Polluted ground water has the potential to contribute to surface-water pollution problems in reservoirs. Ground-water protection can be achieved only through public awareness of the problems associated with ground-water pollution and the potential of various activities to contaminate ground water. Identifying the ground-water resources in a watershed and developing a plan for protection of these resources are critical in establishing a good ground-water protection program. TVA (1988) has found that an extensive public outreach program is instrumental in the development of an effective ground-water protection program and in eventual protection of the resource.

e. Mine Reclamation

Abandoned mines 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 the NPS pollutants emanating from them. Revegetation is a cost-effective method of reclaiming denuded strip-mined lands, and agencies such as the Soil Conservation Service can provide technical insight for revegetation practices.

f. Animal Waste Control

A major contributor to reservoir pollution in some watersheds is wastes 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. A cooperative program was established to address the animal waste problem in the Tennessee Valley. The results of demonstration facilities in the Tennessee Valley reduced NPS pollution from animal wastes by 25,000 tons in the Duck River basin. The program also had the benefit of reducing the additional input of 1,400 tons of nitrogen and 200 tons of phosphorus to farm fields (TVA, 1988). Refer to Chapter 2 of this guidance for additional information on animal waste control practices.

g. Failing Septic Systems

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 information on OSDS practices can be found in Chapter 4.

9. Practices to Restore or Maintain Aquatic and Riparian Habitat

Studies like the one undertaken by the U.S. Department of the Interior (USDOI, 1988) on the Glen Canyon Dam (Colorado River, Colorado) illustrate the potential for disruption to downstream aquatic and riparian habitat resulting from the operation of dams.

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. Flow Augmentation

Operational procedures such as flow regulation, flood releases, or fluctuating flow releases all have a detrimental impact on downstream aquatic and riparian habitat. Confounding the problem of aquatic and riparian habitat restoration is necessary for a balance of 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 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 Nevadas, California, a study found that wild salmonids prefer to deposit their eggs in streambed gravel 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 regimen for removing fine-grained sediments from portions of the Little Snake River that served as instream habitat for Colorado cutthroat trout. 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.

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 the 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).

Minimum flows are needed to keep streambeds wetted to an acceptable depth to support desired fish and wildlife. Since wetlands and riparian areas are linked hydrologically to adjoining streams, instream flows should be sufficient to maintain wetland or riparian habitat and function. Flushing and scouring flows may also be necessary to clean some streambeds and to provide the proper substrate for aquatic species.

In the design, construction, and operation of dams, the minimum flow requirements to support aquatic organisms and other water-dependent wildlife in downstream areas should be addressed. Minimum flow requirements are typically determined to protect or enhance one or a few harvestable species of fish (USDOI-FWS, 1976). 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 (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 (USDOE, 1991).

Flows at Rush Creek on the Eastern slope of the Sierra Nevadas in California have averaged about 50 percent of their prediversion 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. If 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 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.

Several options exist for establishing 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 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) improved 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. Three options (turbine pulsing, sluicing, and 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. (Based on studies cited in a previous section of this chapter, 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 setting turbines on and off frequently (Hauser et al., 1989). Hauser (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 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. Instream habitat for adult brook trout, adult brown trout, and adult rainbow trout was most desirable at discharges in the vicinity of 1,000 to 2,000 cfs (Nestler et al., 1986a).

A reregulation weir was also found to be the most cost-effective alternative for providing a 90-cfs minimum flow below the Holston Dam (South Fork Holston River, Tennessee) for maintenance of instream trout habitat (Adams and Hauser, 1990). The weir was investigated as one alternative for establishing minimum flows, along with 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. The three alternatives were assessed for their effects on river hydraulics and on operation of the hydropower facility.

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).

b. 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 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. These 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).

c. Aquatic Plant Management

One study of the Cherokee Reservoir (Holston River, Tennessee) reveals the potential importance of watershed protection practices for the improvement of water quality in the reservoir (Hauser et al., 1987). An improved two-dimensional model of reservoir water quality was used to investigate the advantages and disadvantages of several practices for improving temperature and DO levels in the reservoir.

10. Practices to Maintain Fish Passage

Migrating fish populations may 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 other 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. Despite extensive research, no single device or system has received regulatory agency approval for general use (Stone and Webster, 1986).

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. Rochester and others (1984) provide an excellent discussion of some of the economic and engineering considerations necessary to address the problems associated with the safe passage of fish.

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 four additional practices that have been successfully used to maintain fish passage: spill and water budgets, fish ladders, transference of fish runs, and constructed spawning beds.

a. 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, with mixed results. The results with system tests of strobe lights, poppers, and hybrid systems are the most promising, but these systems are still in need of further testing (Mattice, 1990). Experiences with some kinds of behavioral barrier systems are described more fully in the following paragraphs.

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 this type of system 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). This type of system requires constant maintenance of the electrodes and the associated underwater hardware in order 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 and rusting. Installation of bubbler systems needs to consider 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 rated 65 to 95 percent effective at repelling or diverting eels (Stone and Webster, 1986). 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).

Mercury lights are used to attract the fish as opposed to repelling them. Studies of mercury lights suggest their effectiveness is species-specific; alewives were attracted to a zone of filtered mercury light, whereas coho salmon and rainbow trout displayed no attraction to mercury light (Stone and Webster, 1986). Insufficient data are available to determine whether mercury lights are lifestage-specific. The device shows promise, but more research is being conducted to determine factors that affect performance and efficiency.

Underwater sound broadcast at different frequencies and amplitudes has been shown to be effective in attracting or repelling fish, although the results of field tests are not consistent. Fish have been attracted, repelled, or guided by the sound, and no conclusive response to sound has been observed. 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, perch, and smelt (Stone and Webster, 1986), 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 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 concerns would be clogging of the jet nozzles by debris or rust and the acceptable range of flow conditions.

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 90 percent effective at repelling fish. Combinations of rope-net and chain-rope barriers have also been tested with good results. Barriers with horizontal components 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).

▨ b. Physical Barriers

Physical barriers such as barrier nets and stationary screens can prevent the entry of fish and other aquatic organisms into the intakes at a generating facility. However, they should not be regarded as having much potential for application to promote fish bypass at hydroelectric dams for two reasons. First, the size of the mesh and the labor-intensive maintenance required to remove water-borne trash lower the feasibility of their use. Second, these barriers do little to assist fish in bypassing dams during migration (Mattice, 1990).

▨ c. Fish Collection Systems

Collection systems involve capture of fish by screening and/or netting followed by transport by truck or barge to a downstream location (Figure 6-8). Since the late 1970s, the Corps of Engineers 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 implemented (see below) when the collection rate achieves less than 70 percent efficiency (Dodge, 1989).

▨ d. Fish Diversion Systems

Diversion systems lead or force fish to bypasses that transport them to the natural waterbody below the dam (USEPA, 1979). Physical diversion structures deployed at dams include traveling screens, louvers, angled screens, drum screens, and inclined plane screens. Most of these systems have been effectively deployed at specific hydropower facilities. However, a sufficient range of performance data is not yet 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 and adult 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 this device can vary by species, approach velocity, fish length, screen mesh size,screen type, and temperature (Stone and Webster, 1986).

Angled rotary drum screens oriented perpendicular to the flow direction have been used extensively to lead fish to a bypass. They have not experienced major operational and maintenance problems. Maintenance 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 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. They operate by creating turbulence that fish are able to detect and avoid (Stone and Webster, 1986).

Submerged traveling screens are used to divert downstream migrating fish out of turbine intakes to adjoining gatewell structures, where they are concentrated for release downstream (Figure 6-9). 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).

e. Spill and Water Budgets

Although used together, spill and water budgets are independent methods of facilitating downstream fish migration.

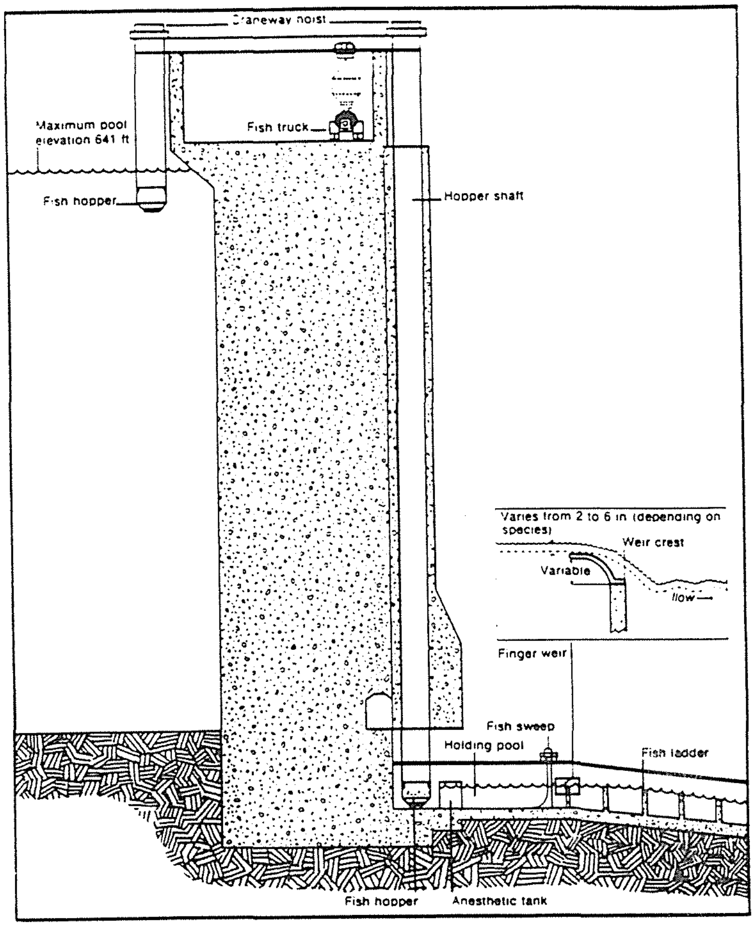


Figure 6-8. Trap and haul system for fish bypass of the Foster Dam, Oregon (Nelson et al., 1978).

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 benefits is lacking (Dodge, 1989).

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 Corps of Engineers 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 Corps of Engineers model called FISHPASS, show 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).

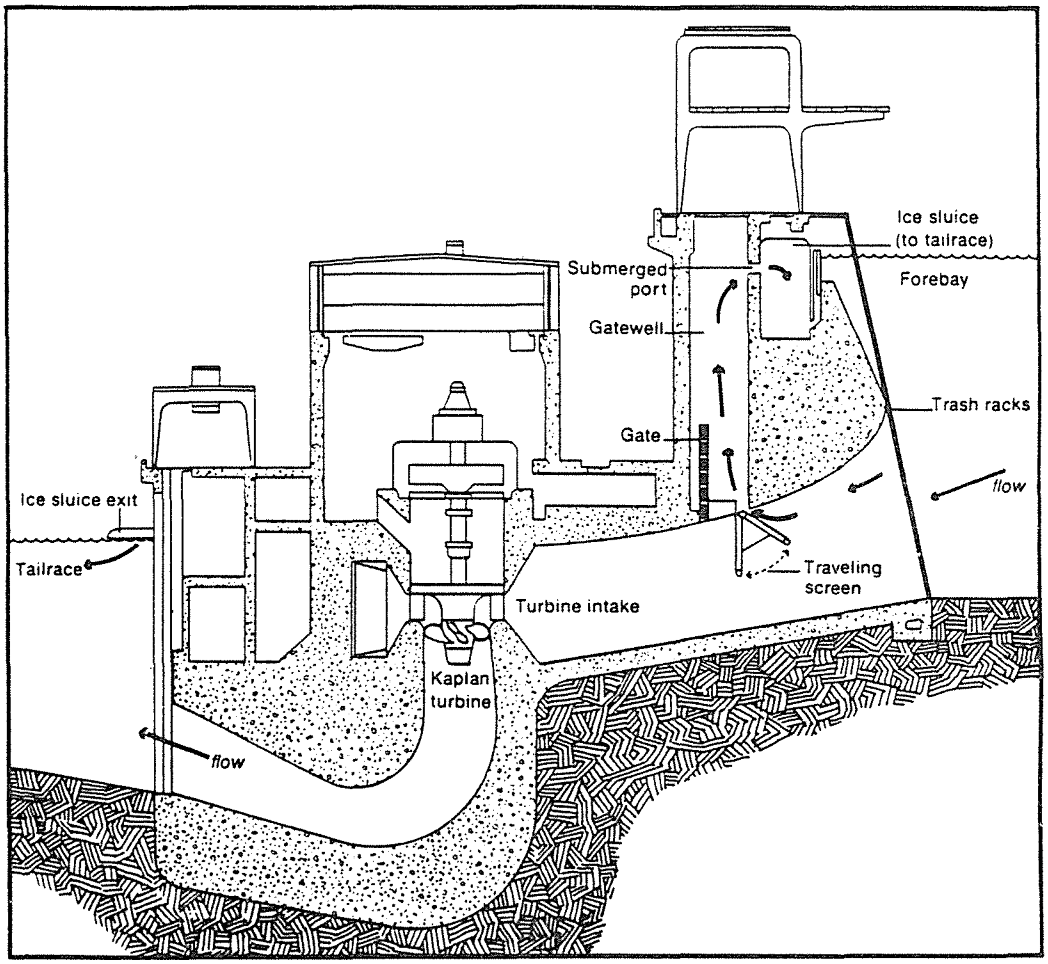


Figure 6-9. Cross section of a turbine bypass system used at Lower Granite and Little Goose Dams, Washington (Nelson et al., 1978).

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).

f. *Fish Ladders*

Fish ladders are one type of structure that can be provided to enable the safe upstream and downstream passage of mature fish. One such installation in Maine consists of a vertical slot fishway, constructed parallel to the tailrace, which allows fish to pass from below the dam to the headwaters (ASCE, 1986). The fishway consists of a series of pools, each 8.5 feet by 10 feet in size, which ascend in 1-foot increments through the 40-foot rise from the tailwater area to the headwater area. When there is no flow in the spillway, fish can pass downstream through an 18-inch pipe. Flow is provided in the tailrace during fish migration season. Fish prefer to travel in these fishways at night under low illumination (Larinier and Boyer-Bernard, 1991).

Information on the effectiveness of these types of structures is scarce and inconclusive, according to a study by the General Accounting Office (GAO, 1990). GAO noted that many studies of bypass facilities have emphasized data collection to document the number of juvenile fish entering the bypass structures and the condition of the individuals after passage is completed. Only two studies were identified in which bypass methods were compared with alternative methods to identify the most successful approaches. The observations collected at Lower Granite Dam and at Bonneville Dam (Columbia River) indicate a higher survival rate for young fish passing through turbines than for those passing through a bypass structure.

▨ g. 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. One case where an ephemeral stream was used to convey water and create alternative instream habitat for fish is along South Fort Crow Creek, in Medicine Bow National Forest, Wyoming. After 2 years of diversion, the amount of stream channel on an 88-km reach had increased 32 percent. Some measure of the success with which alternative instream habitat has replaced the original conditions can be seen in the total area of beaver ponds, which doubled within 2 years of completion of the project (Wolff et al., 1989).

▨ h. Constructed Spawning Beds

When the adverse effects of a dam on the aquatic habitat of an anadromous fish species are severe, one option may be to construct suitable replacement spawning beds (Virginia State Water Control Board, 1979). Additional facilities such as electric barriers, fish ladders, or bypass channels will have to be furnished to channel the fish to these spawning beds.

11. Costs for All Practices

a. Costs for Minimum Flow Alternatives

In a comparisons of costs of minimum flows alternatives at South Fork Holston River, Adams and Hauser (1990) describe costs for a variety of practices, including an estimated total direct cost of $539,000 for a reregulating weir and $1,258,000 for a small hydro unit.

b. Costs for Hypolimnetic Aeration

The diffused air system is generally the most cost-effective method to raise low DO levels (Henderson and Shields, 1984; Cooke and Kennedy, 1989). However, the costs of air diffuser operation may be high for deep reservoirs because of hydraulic pressures that must be overcome. Any destratification that results from deployment of an air diffuser system will 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. The mixing must be complete to avoid problems with algal blooms (Cooke and Kennedy, 1989).

Fast and others (1976) and Lorenzen and Fast (1977) discuss costs of hypolimnetic aeration. The following are capital cost items for aeration systems: air lift devices, the compressor, the air supply lines, and the diffusers. The costs for these items are dependent on aerator size, which in turn is dependent on the need for oxygen in the reservoir impoundment (McQueen and Lean, 1986). Cooke and Kennedy (1989) reported side stream pumping costs (adjusted to 1990 dollars) were $347,023 (capital costs) and $167,240 (yearly operation and maintenance costs). Partial air lift system costs (adjusted to 1990 dollars) were reported by Cooke and Kennedy (1989) as $627,150 (capital costs) and $105,257 (operation and maintenance costs). Capital costs for full air lift systems ranged (in 1990 dollars) from $250,860 to $585,340, and operation and maintenance costs (in 1990 dollars) were reported as $44,862 (Cooke and Kennedy, 1989). In the opinion of Cooke and Kennedy (1989), the full air lift system is the least costly to operate and the most efficient. Furthermore, there is the potential for surface water quality problems caused by the supersaturation of nitrogen gas with the use of the partial air lift system (Fast et al., 1976). Accordingly, the full air lift system seems to be the overall best choice for aeration, based on cost, efficiency, and environmental impacts.

c. Costs for Diffusers

A cost-effective means of achieving better water quality for reservoir releases is to aerate discrete layers near the intakes to avoid any unnecessary release of algae and nutrients into tailwaters below the dam. In another test at facilities operated by the Tennessee Valley Authority (TVA), diffusers were deployed at the 70-foot depth of Fort Patrick Henry Dam near one of the turbine intakes. Levels of DO in the tailwaters increased from near zero to 4 mg/L as a result of operation of this aeration system. Unfortunately, the operation costs of this kind of system were determined to be relatively high. An operation system to increase the 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 (Harshbarger, 1987).

The TVA has determined that approximately $44 million would be required to purchase and install aeration equipment at 16 TVA facilities (TVA, 1990). The aeration of reservoir waters, combined with other practices such as turbine pulsing, would result in the recovery of over 180 miles of instream habitat in areas below TVA dams. An additional $4 million per year in annual operating costs would also be required.

d. Costs for Aeration Weirs

The estimated costs for an aeration weir constructed downstream of the Canyon Dam (Guadalupe River, Texas) were $60,000. However, the construction of this device occurred at the same time as other construction at the facility, resulting in a reduction in overall project costs (EPRI, 1990).

e. Costs for Fish Bypass System

The Philadelphia Electric Company installed a fish lift system on the Conowingo Dam, located on the Susquehanna River at the head of the Chesapeake Bay. The fish lift system has the capacity of lifting 750,000 shad and 5 million river herring per year. The system was completed in 1991 at a total cost (adjusted to 1990 dollars) of $11.9 million (Nichols, 1992).

IV. STREAMBANK AND SHORELINE EROSION MANAGEMENT MEASURE

Streambank erosion is used in this guidance to refer to the loss of fastland along nontidal streams and rivers. *Shoreline erosion* is used in this guidance to refer to the loss of beach or fastland in tidal portions of coastal bays or estuaries. Erosion of ocean coastlines is not regarded as a substantial contributor of NPS pollution in coastal waterbodies and will not be considered in this guidance.

The force of water flowing in a river or stream can be regarded as the most important process causing erosion of a streambank. All of the eroded material is carried downstream and deposited in the channel bottom or in point bars located along bends in the waterway. The process is very different in coastal bays and estuaries, where waves and currents can sort the coarser-grained sands and gravels from eroded bank materials and move them in both directions along the shore, through a process called *littoral drift*, away from the area undergoing erosion. Thus, the materials in beaches of coastal bays and estuaries are derived from shore erosion somewhere else along the shore. Solving the erosion of the source area may merely create new problems with beach erosion over a much wider area of the shore.

The seepage of ground water and the overland flow of surface water runoff also contribute to the erosion of both streambanks and shorelines. The role of ground water is most important wherever permeable subsurface layers of sand or gravel are exposed in banks and high bluffs along streams, rivers, and coastal bays (Palmer, 1973; Leatherman, 1986; Figure 6-10). In these areas, the seepage of ground water into the waterway can cause erosion at the point of exit from the bank face, leading to bank failure. The surface flow of upland runoff across the bank face can also dislodge sediments through sheet flow, or through the creation of rills and gullies on the shoreline banks and bluffs.

The erosion of shorelines and streambanks is a natural process that can have either beneficial or adverse impacts on the creation and maintenance of riparian habitat. Sands and gravels eroded from streambanks are deposited in the channel and are used as instream habitat during the life stages of many benthic organisms and fish. The same materials eroded from the shores of coastal bays and estuaries maintain the beach as a natural barrier between the open water and coastal wetlands and forest buffers. Beaches are dynamic, ephemeral land forms that move back and forth onshore, offshore, and along shore with changing wave conditions (Bascom, 1964). The finer-grained silts and clays derived from the erosion of shorelines and streambanks are sorted and carried as far as the quiet waters of wetlands or tidal flats, where benefits are derived from addition of the new material.

There are also adverse impacts from shoreline and streambank erosion. Excessively high sediment loads can smother submerged aquatic vegetation (SAV) beds, cover shellfish beds and tidal flats, fill in riffle pools, and contribute to increased levels of turbidity and nutrients. However, there are few research results that can be used to identify levels below which streambank and shoreline erosion is beneficial and above which it is an NPS-related problem.

The Chesapeake Bay is one coastal waterbody for which sufficient data exist to characterize the relative importance of shore erosion as a source of sediment and nutrients (Ibison et al., 1990, 1992). Erosion of the shores above mean sea level contributes 6.9 million cubic yards of sediment per year, or 39 percent of the total annual sediment supply to the Chesapeake Bay (USACE, 1990). The contribution of nitrogen from shore erosion is estimated at 3.3 million pounds per year, which is 3.3 percent of the total nonpoint nitrogen load to the Bay. The contribution of phosphorus from shore erosion is estimated at 4.5 million pounds per year, which is approximately 46 percent of the total nonpoint phosphorus load to the Bay (USEPA-CBP, 1991).

For many watersheds, it will be necessary to consider four questions about streambank and shoreline erosion simultaneously in developing an NPS pollution reduction strategy:

(1) Is sediment derived from coastal erosion helping to maintain aquatic habitat elsewhere in the system?

(2) Is coastal erosion a significant contributor of nonpoint sediment and nutrients?

(3) Is coastal erosion causing a loss of wetlands and riparian areas, with resultant loss of aquatic habitat and reduction of capacity to remove NPS pollutants from surface waters?

(4) Are activities along the shoreline and in adjacent surface waters increasing the rate of coastal erosion above natural (background) levels?

The answers to these questions will determine the emphasis that should be given to each of the three elements in the Management Measure for Eroding Streambanks and Shorelines.

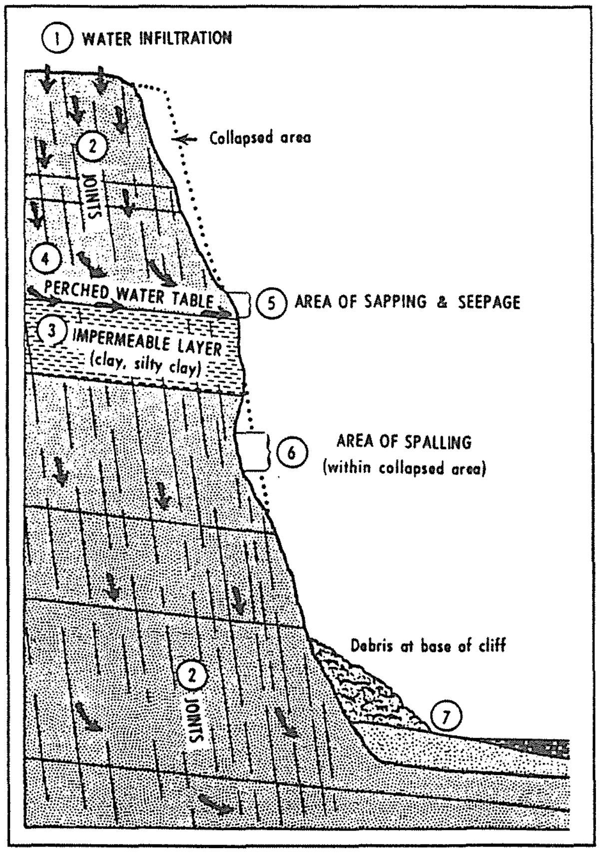


Figure 6-10. The physical processes of bluff erosion in a coastal bay. 1. Water enters the ground by infiltration of rainwater or snowmelt. 2. Nearly vertical cracks called joints aid the downward movement of water. 3. Water moves toward the cliff face upon reaching an impermeable layer of sediment formed by clay. 4. A perched water table forms above the clay layer; the overlying sandy sediments become saturated with water. 5. As water seeps out of the cliff and runs down the cliff face, it may erode the sandy sediments above the clay layer, in a process called *sapping*. 6. *Spalling* is another process by which the bluff face breaks off along a more or less planar surface roughly parallel to the face. Spalling is continuous throughout the year, but it intensifies during the winter months when freezing and thawing occur along the joints and seepage zones. 7. Wave action at the base removes fallen debris, allowing cliff failure to continue. (After Leatherman, 1986.)

A. Management Measure for Eroding Streambanks and Shorelines

(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 cost-effective, considering the severity of wave and wind erosion, 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.

1. Applicability

This management measure is intended to be applied by States to eroding shorelines in coastal bays, and to eroding streambanks in coastal rivers and creeks. The measure does not imply that all shoreline and streambank erosion must be controlled. Some amount of natural erosion is necessary to provide the sediment for beaches in estuaries and coastal bays, for point bars and channel deposits in rivers, and for substrate in tidal flats and wetlands. The measure, however, applies to eroding shorelines and streambanks that constitute an NPS problem in surface waters. It is not intended to hamper the efforts of any States or localities to retreat rather than to harden the shoreline. Under the Coastal Zone Act Reauthorization Amendments of 1990, States are subject to a number of requirements as they develop coastal NPS programs in conformity with this measure and will have some flexibility in doing so. The application of management measures by States is described more fully in *Coastal Nonpoint Pollution Control Program: Program Development and Approval Guidance*, published jointly by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

2. Description

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 other cases, the use of engineering approaches, including beach nourishment or coastal structures, may need to be considered. In addition to controlling those sources of sediment input to surface waters which are causing NPS pollution, these techniques can halt the destruction of wetlands and riparian areas located along the shorelines of surface waters. Once these features are protected, they can serve as a filter for surface water runoff from upland areas, or as a sink for nutrients, contaminants, or sediment already present as NPS pollution in surface waters.

Stabilization practices involving vegetation or coastal engineering should be properly designed and installed. These techniques should be applied only when there will be no adverse effects to aquatic or riparian river habitat, or to the stability of adjacent shorelines, from stabilizing a source of shoreline sediments. Finally, it is the intent of this measure to promote institutional measures that establish minimum set-back 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.

3. Management Measure Selection

This management measure was selected for the following reasons:

(1) Erosion of shorelines and streambanks contributes significant amounts of NPS pollution in surface waters such as in the Chesapeake Bay;

(2) 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; and

(3) A variety of activities related to the use of shorelands or adjacent surface waters can result in erosion of land along coastal bays or estuaries and losses of land along coastal rivers and streams.

4. Practices

As discussed more fully at the beginning of this chapter and in Chapter 1, the following practices are described for illustrative purposes only. State programs need not require the implementation of these practices. However, as a practical matter, EPA anticipates that the management measure set forth above generally will be implemented by applying one or more management practices appropriate to the source, location, and climate. The practices set forth below have been found by EPA to be representative of the types of practices that can be applied successfully to achieve the management measure described above.

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.

▨ a. *Use soil bioengineering and other vegetative techniques to restore damaged habitat along shorelines and streambanks wherever conditions allow.*

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-SCS, 1992). 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-SCS, 1992).

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 (Schiechtl, 1980; Gray and Leiser, 1982; Porter, 1992).

Specific soil bioengineering practices include (USDA-SCS, 1992):

- **Live Staking.** Live staking involves the insertion and tamping of live, rootable vegetative cuttings into the ground (Figure 6-11). 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. Most willow species are ideal for live staking because they root

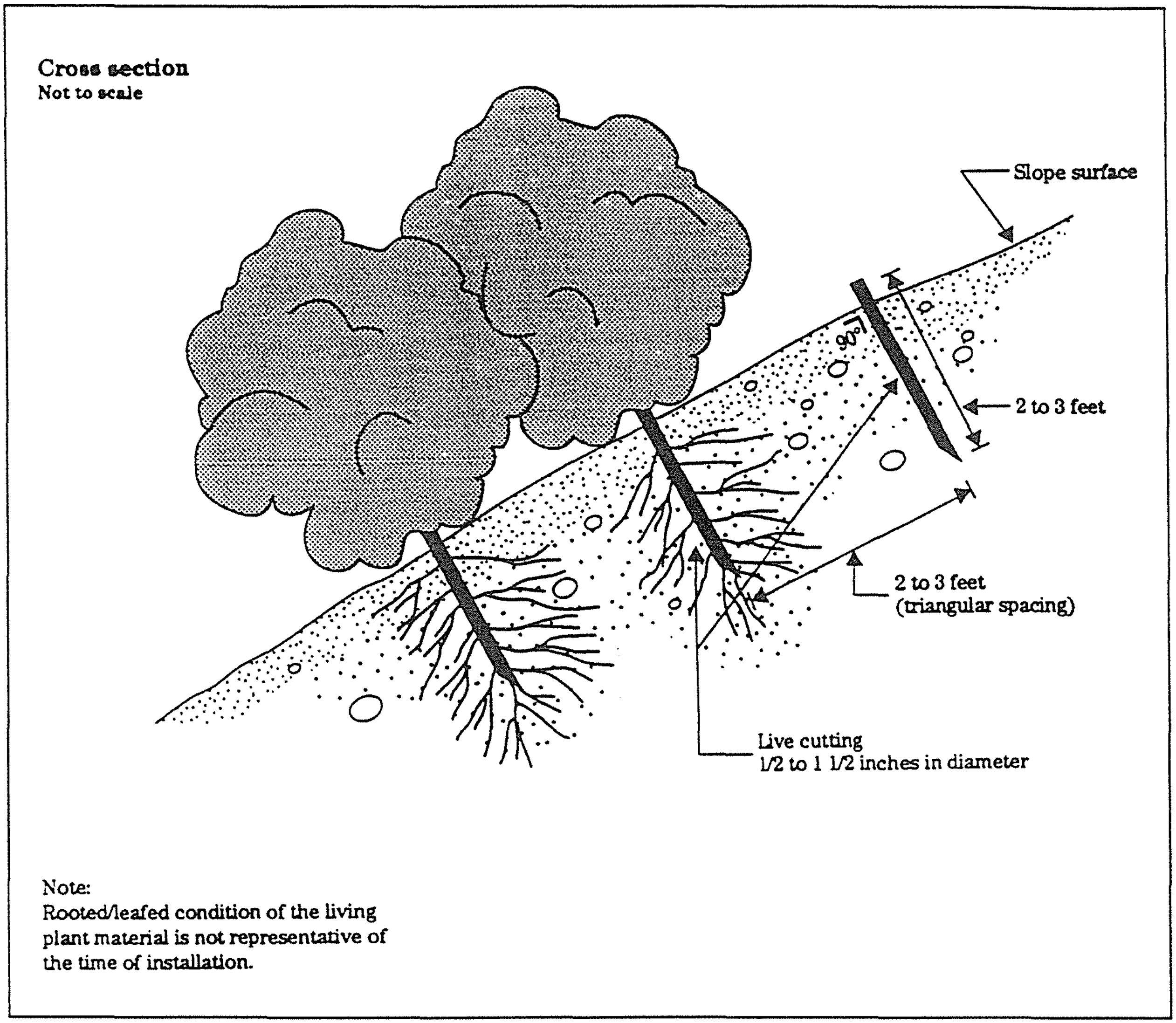


Figure 6-11. Schematic cross section of a live stake installation showing important design elements (USDA-SCS, 1992).

rapidly and begin to dry out a slope soon after installation. This is an appropriate technique for repair of small earth slips and slumps that frequently are wet.

- **Live Fascines.** Live fascines are long bundles of branch cuttings bound together into sausage-like structures (Figure 6-12). When cut from appropriate species and properly installed, they will root and immediately begin to stabilize slopes. They should be placed in shallow contour trenches on dry slopes and at an angle on wet slopes to reduce erosion and shallow face sliding. This system, installed by a trained crew, does not cause much site disturbance.

- **Brushlayering.** Brushlayering consists of placing live branch cuttings in small benches excavated into the slope. The width of the benches can range from 2 to 3 feet. The portions of the brush that protrude from the slope face assist in retarding runoff and reducing surface erosion. Brushlayering 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 brushlayering, the cuttings are oriented more or less perpendicular to the slope

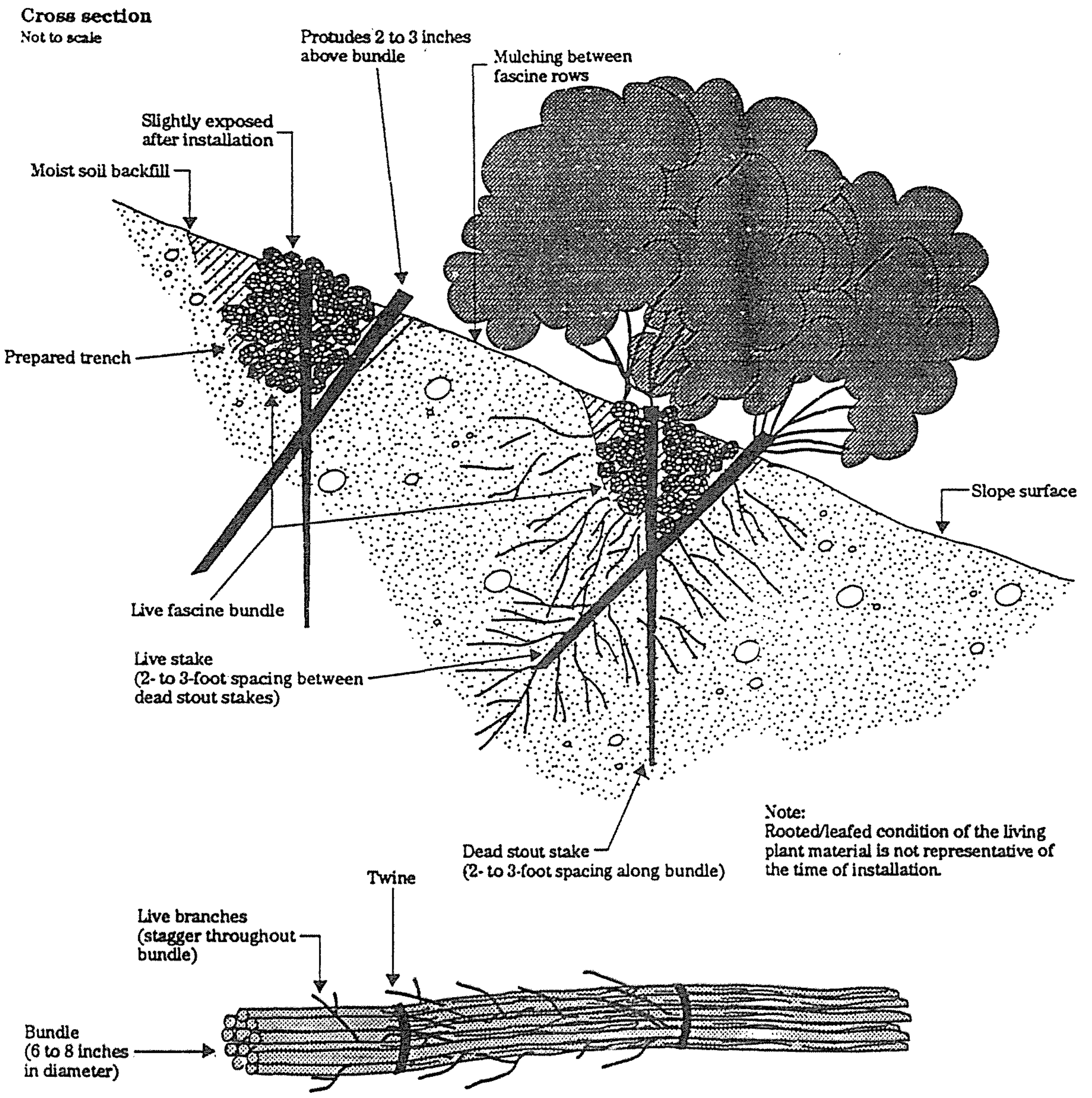


Figure 6-12. Schematic cross section of a live fascine showing important design elements (USDA-SCS, 1992).

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.

- **Brush Mattressing.** Brush mattressing is commonly used in Europe for streambank protection. It involves digging a slight depression on the bank and creating a mat or mattress from woven wire or single strands of wire and live, freshly cut branches from sprouting trees or shrubs. Branches up to 2.5 inches in diameter are normally cut 3 to 10 feet long 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 up to 3 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.

- **Branchpacking.** Branchpacking consists of alternating layers of live branch cuttings and compacted backfill to repair small localized slumps and holes in slopes (Figure 6-13). Live branch cuttings may range from 1/2 inch 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. As plant tops begin to grow, the branchpacking 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.

- **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 6-14). Alternatively, the cuttings can be tamped into place at the same time that rock is being placed on the slope face.

- **Live Cribwalls.** A live cribwall consists of a hollow, box-like interlocking arrangement of untreated log or timber members (Figure 6-15). 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. Once the live cuttings root

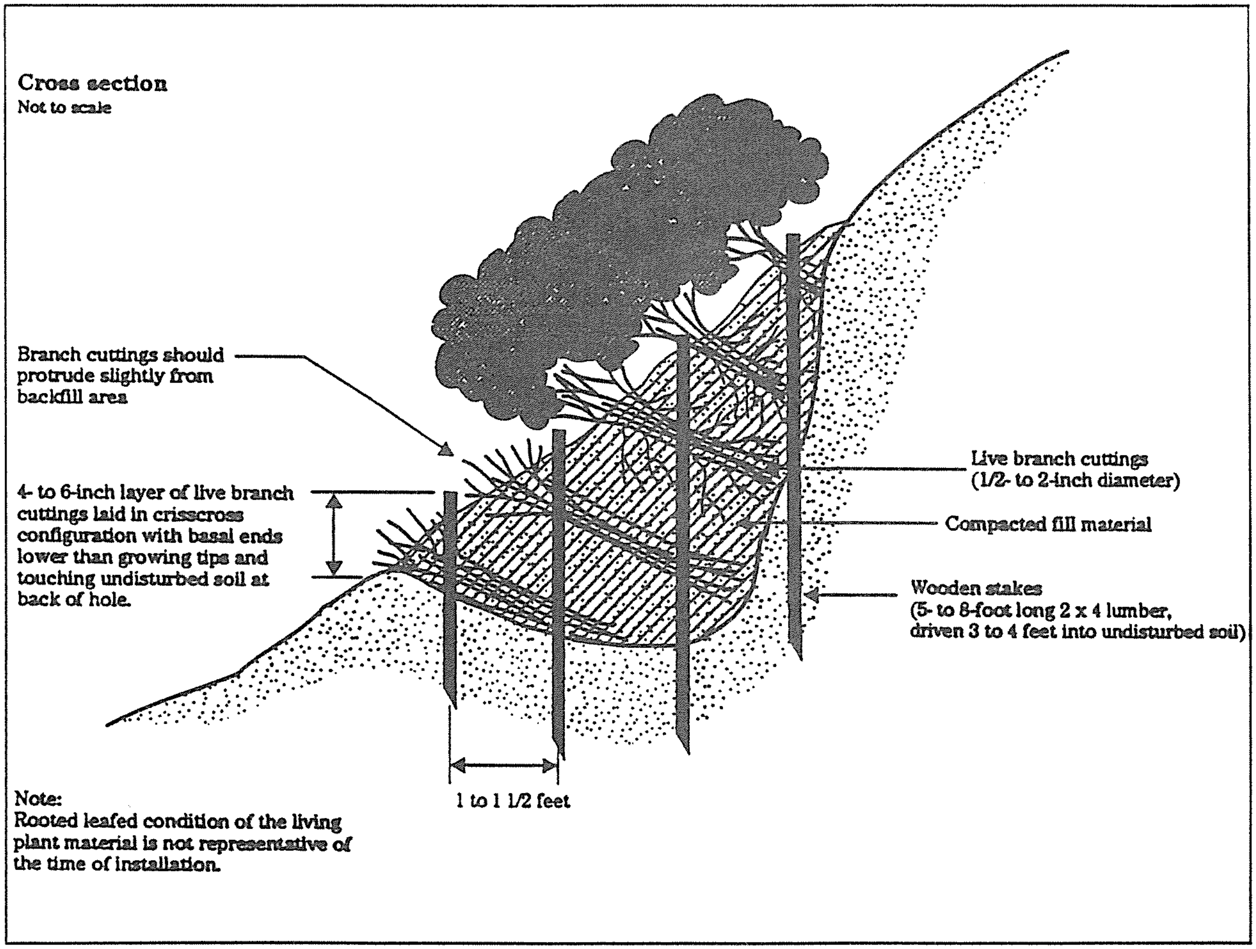
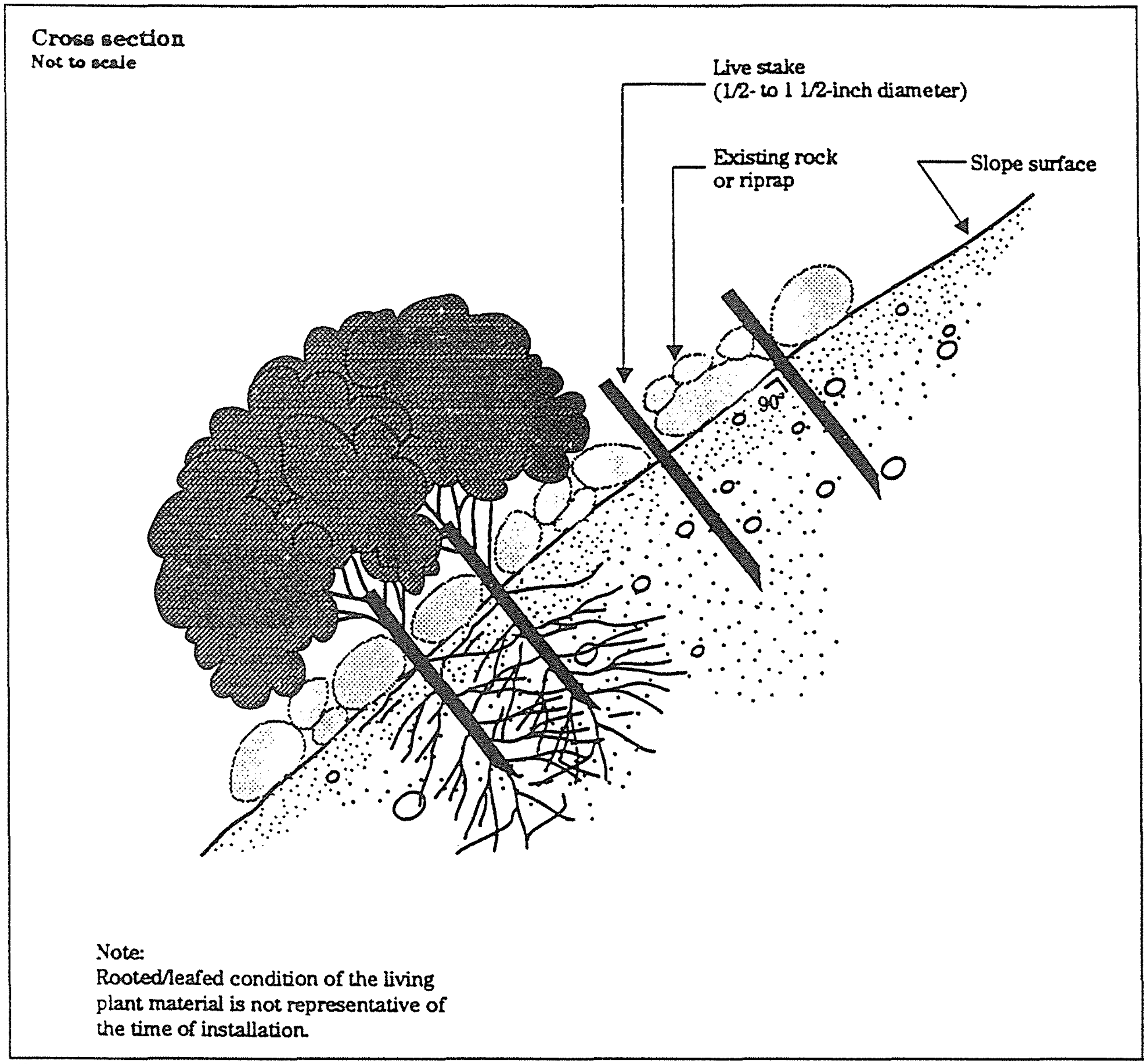


Figure 6-13. Schematic cross section of a branchpacking system showing important design details (USDA-SCS, 1992).



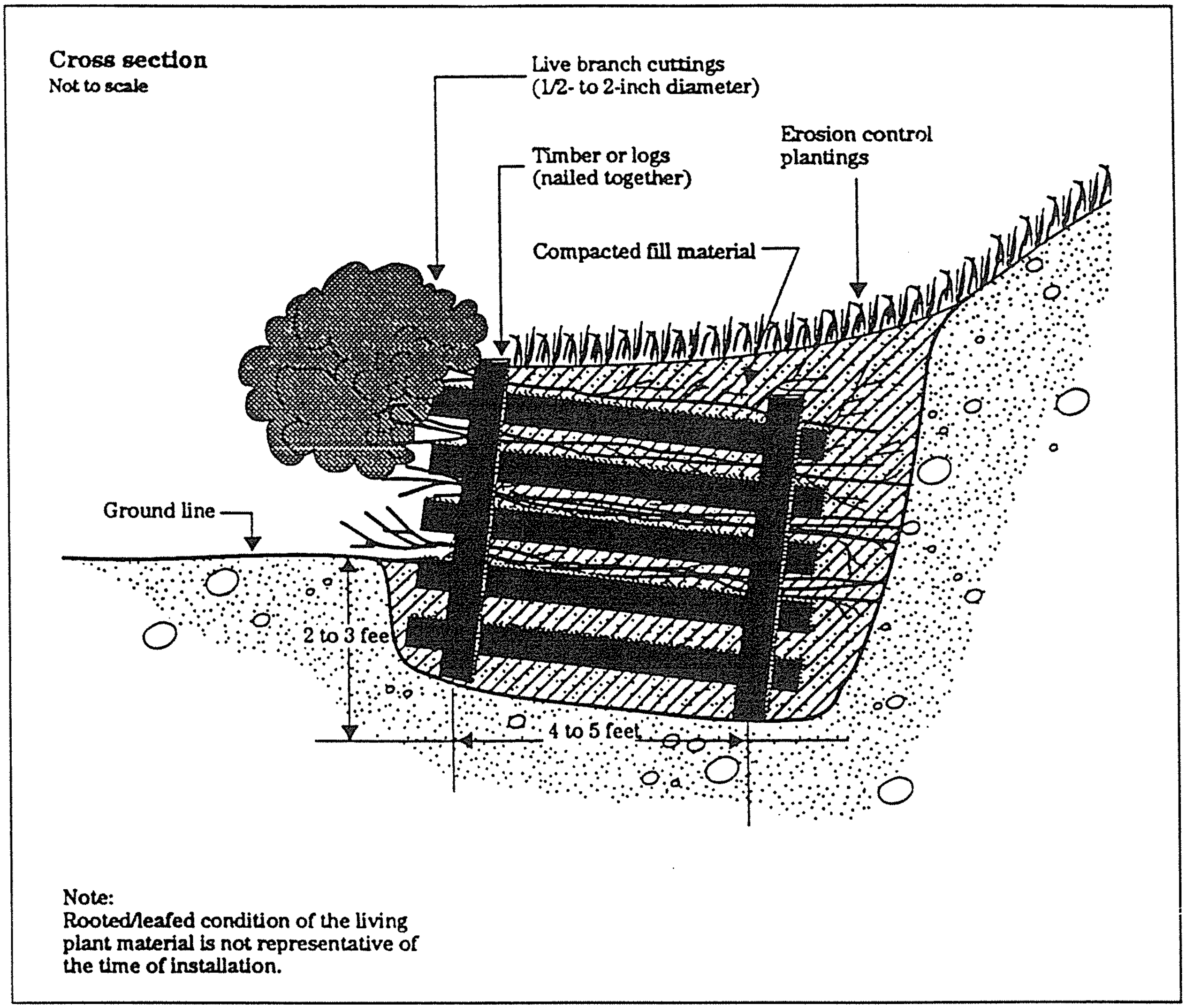
Note:
Rooted/leafed condition of the living plant material is not representative of the time of installation.

Figure 6-14. Schematic cross section of a joint planting system showing important design elements (USDA-SCS, 1992).

and become established, the subsequent vegetation gradually takes over the structural functions of the wood members.

These 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 in the last two decades, 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).



Note:
Rooted/leafed condition of the living plant material is not representative of the time of installation.

Figure 6-15. Schematic cross section of a live cribwall showing important design elements (USDA-SCS, 1992).

Local agencies such as the USDA Soil Conservation Service and Extension Service can be a useful source of information on appropriate native plant species that can be considered for use in bioengineering projects (USDA-SCS, 1992). For the Great Lakes, the U.S. Army Corps of Engineers 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).

When considering a soil bioengineering approach to shoreline stabilization, several factors in addition to selection of plant materials are important. Shores subject to wave erosion will usually require structures or beach nourishment to dampen wave energy. In particular, the principles of soil bioengineering, discussed previously, will 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 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 more gentle slope to accommodate the plant material (Hall and Ludwig, 1975).

Marsh creation and restoration is another useful vegetative technique that can be used to address problems with erosion of coastal 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, both 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 erosion of the shore. Second, marsh plants form a dense mat of roots (called rhizomes), which can add stability to the shoreline sediments.

Techniques of marsh creation for shore erosion control have been described by researchers for various coastal areas of the United States, including North Carolina (Woodhouse et al., 1972; Knutson, 1977; Knutson and Inskeep, 1982; Knutson and Woodhouse, 1983), the Chesapeake Bay (Garbisch et al., 1973; Sharp et al., undated), and Florida and the Gulf Coast (Lewis, 1982). The basic approach 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 (see practice b below), 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 (Figure 6-16) or in a series of breakwaters (Figure 6-17).

Knutson and Woodhouse (1983) have developed a method for evaluating the suitability of shoreline sites for successful creation of marshes. The method uses a Vegetative Stabilization Site Evaluation Form (Figure 6-18) to evaluate potential for planting success on a case-by-case basis. The user measures each of four characteristics for the area in question, identifies the categories on the form that best describe the area, calculates a cumulative score, and uses the score to determine the potential success rate for installation of wetland plants in the intertidal zone. Sites with a cumulative score of 300 or greater have been correlated with 100 percent success rates at actual field planting sites (Lewis, 1982). Sites with scores between 201 and 300 generally have a success rate of 50 percent, which often constitutes an acceptable risk for undertaking a shoreline erosion control project emphasizing marsh creation (Lewis, 1982).

■ *b. Use properly designed and constructed engineering practices for shore erosion control in areas where practices involving marsh creation and soil bioengineering are ineffective.*

Properly designed and constructed shore and streambank erosion control structures are used in areas where higher wave energy makes biostabilization and marsh creation ineffective. There are many sources of information

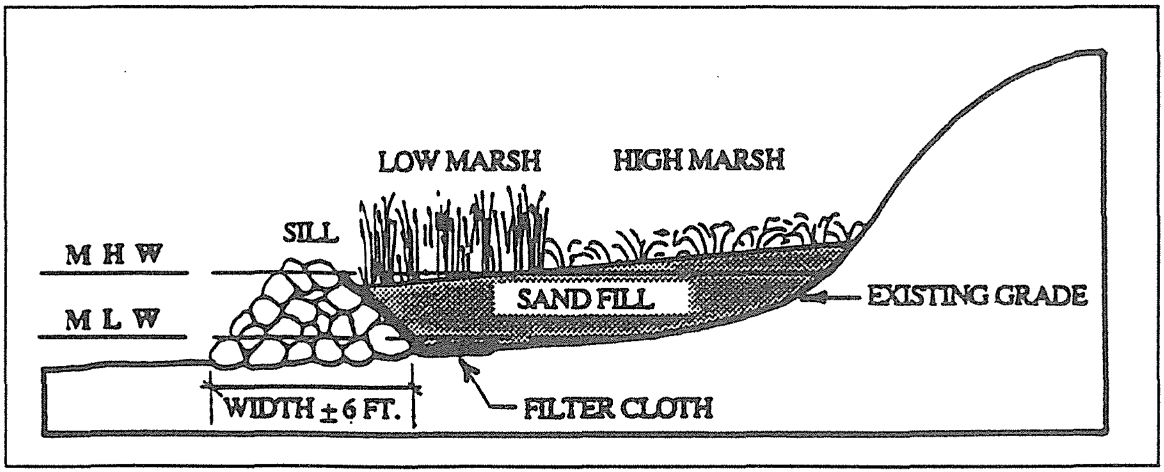


Figure 6-16. Continuous stone sill protecting a planted marsh (Environmental Concern, Inc., 1992).

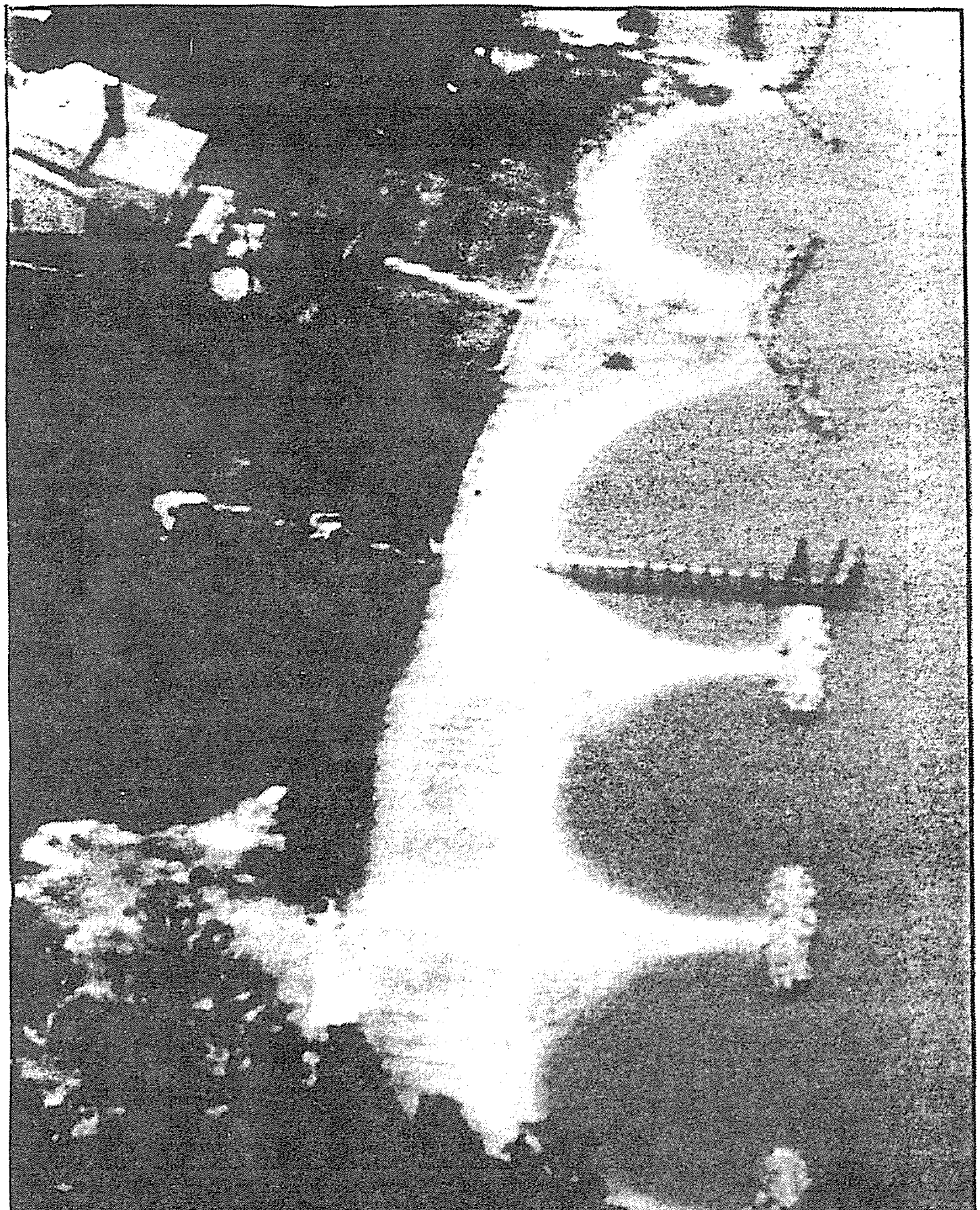
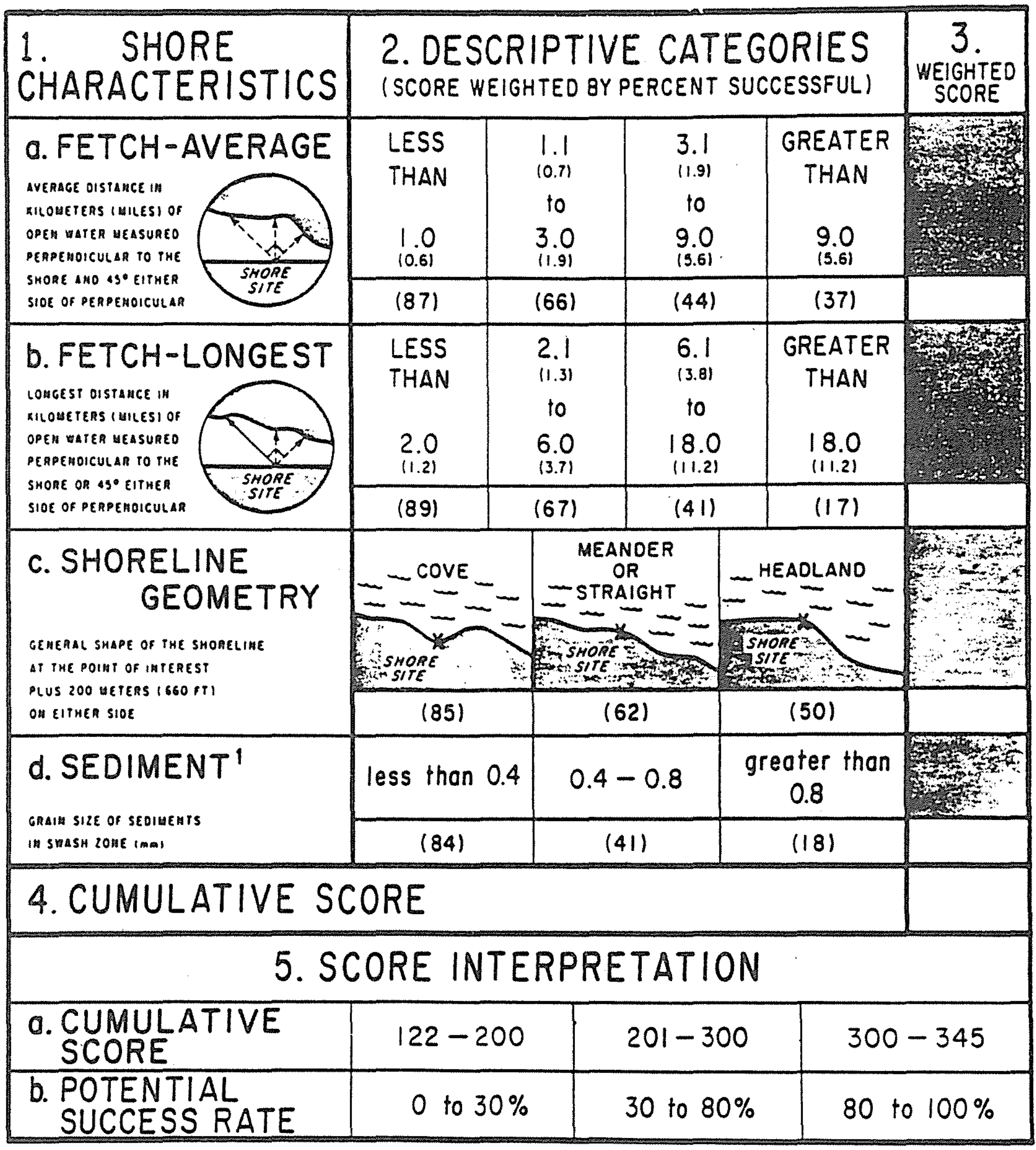


Figure 6-17. Headland breakwater system at Drummonds Field, Virginia. The breakwaters control shoreline erosion and provide a community beach. (Hardaway and Gunn, 1991.)

concerning the proper design and construction of shoreline and streambank erosion control structures. Table 6-4 contains several useful sources of design information. 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):



1. SHORE CHARACTERISTICS	2. DESCRIPTIVE CATEGORIES (SCORE WEIGHTED BY PERCENT SUCCESSFUL)				3. WEIGHTED SCORE
a. FETCH-AVERAGE AVERAGE DISTANCE IN KILOMETERS (MILES) OF OPEN WATER MEASURED PERPENDICULAR TO THE SHORE AND 45° EITHER SIDE OF PERPENDICULAR	LESS THAN 1.0 (0.6)	1.1 (0.7) to 3.0 (1.9)	3.1 (1.9) to 9.0 (5.6)	GREATER THAN 9.0 (5.6)	
	(87)	(66)	(44)	(37)	
b. FETCH-LONGEST LONGEST DISTANCE IN KILOMETERS (MILES) OF OPEN WATER MEASURED PERPENDICULAR TO THE SHORE OR 45° EITHER SIDE OF PERPENDICULAR	LESS THAN 2.0 (1.2)	2.1 (1.3) to 6.0 (3.7)	6.1 (3.8) to 18.0 (11.2)	GREATER THAN 18.0 (11.2)	
	(89)	(67)	(41)	(17)	
c. SHORELINE GEOMETRY GENERAL SHAPE OF THE SHORELINE AT THE POINT OF INTEREST PLUS 200 METERS (660 FT) ON EITHER SIDE	COVE	MEANDER OR STRAIGHT	HEADLAND		
	(85)	(62)	(50)		
d. SEDIMENT[1] GRAIN SIZE OF SEDIMENTS IN SWASH ZONE (mm)	less than 0.4	0.4 – 0.8	greater than 0.8		
	(84)	(41)	(18)		
4. CUMULATIVE SCORE					

5. SCORE INTERPRETATION

a. CUMULATIVE SCORE	122 – 200	201 – 300	300 – 345
b. POTENTIAL SUCCESS RATE	0 to 30%	30 to 80%	80 to 100%

[1] Grain-size scale for the Unified Soils Classification (Casagrande, 1948; U.S. Army Engineer Waterways Experiment Station, 1953):

Clay, silt, and find sand - 0.0024 to 0.42 millimeter
Medium sand - 0.42 to 2.0 millimeters
Coarse sand - 2.0 to 4.76 millimeters.

Figure 6-18. Vegetative Stabilization Site Evaluation Form (Knutson and Woodhouse, 1983).

Table 6-4. Sources for Proper Design of Shoreline and Streambank Erosion Control Structures

Index	Source	Location	Practices
1	USDA, Soil Conservation Service. 1985. *Streambank and Shoreline Protection.*	United States	• removal of debris • reduction of slope • heavy stone placement • deflectors • vegetation protection
2	Henderson, J.E. 1986. Environmental Designs for Streambank Protection Projects. *Water Resources Bulletin*, 22 (4) 549-558.	United States	• vegetative shoreline stabilization • structural shoreline stabilization
3	Porter, D.L. 1992. *Light Touch, Low Cost, Streambank and Shoreline Erosion Control Techniques.* Tennessee Valley Authority.	Tennessee	• piling revetment • tree revetment and breakwaters • board fence revetments and dikes • tire post retards and revetments • wire cribs • floating tire breakwater • sand bag revetment • toe protection • brush mat revetment • log and cable revetment • vegetative plantings
4	U.S. Army Corps of Engineers. 1983. *Streambank Protection Guidelines for Landowners and Local Governments.* Vicksburg, MS.	United States	• planning/land use management • stream rerouting • removal of obstructions • bed scour control • vegetative stabilization • bank shaping • gabions and wire mattresses • rubble • sacks • blocks • fences • kellner jacks • bulkheads • dikes
5	Hill, Lambert, and Ross. 1983. *Best Management Practices for Shoreline Erosion Control.* Virginia Cooperative Extension Service. Publication 447-004.	Virginia	• management of shorelines to prevent erosion • vegetative covers • bank grading • marsh creation • grassed filter strips
6	Gutman, A.L. 1979. Low-cost Shoreline Protection in Massachusetts. In *Proceedings of the Specialty Conference on Coastal Structures 1979*, Alexandria, VA, March 14-16, 1979.	Massachusetts	• sand-filled fabric bags

Table 6-4. (Continued)

Index	Source	Location	Practices
7	Graham, J.S. 1983. Design of Pressure-treated Wood Bulkheads. In *Coastal Structures '83*. U.S. Army Corps of Engineers.	United States	• wood bulkheads/retaining walls
8	Cumberland County SWCD, Knox-Lincoln SWCD, Maine Department of Environmental Protection, Maine Soil and Water Conservation Commission, Portland Water District, Time and Ride RC and D, USEPA, and USDA-SCS. Fact Sheet Series (2, 3, 4, 5, 8, 9, 10, 12)	Maine	• vegetative dune stabilization • vegetative streambank stabilization • vegetated buffer strips • culverts • grassed swales • diversion • minimization of cut and fill • structures to channelize water down steep slopes • shoreline riprap • streambank riprap • temporary check dams
9	Gloucester County, Virginia, Department of Conservation and Recreation, Division of Soil and Water Conservation, Shoreline Programs Bureau. June 1991. *Gloucester County Shoreline Erosion Control Guidance (Draft).*	Gloucester County, VA	• marsh establishment • bank grading and revegetation • riprap revetment • bulkheading • groins • gabions
10	Ehrlich, L.A., and F. Kulhawy. 1982. *Breakwaters, Jetties and Groins: A Design Guide.* New York Sea Grant Institute, Coastal Structures Handbook Series.	New York	• breakwaters • jetties • groins • mound structures • wall structures • longard tubes • sand-filled bags • rock mastic • precast concrete units
11	Saczynski, T.M., and F. Kulhawy. 1982. *Bulkheads.* New York Sea Grant Institute, Coastal Structures Handbook Series.	New York	• anchored walls • cantilevered walls • walls in clay
12	U.S. Army Corps of Engineers, Waterways Experimental Station. *Shoreline Protection Manual,* Volumes I and II. Vicksburg, MS.	United States	• seawalls and bulkheads • revetments • beach fill • groins • jetties • breakwaters

Table 6-4. (Continued)

Index	Source	Location	Practices
13	Fulford, E.T. 1985 *Reef Type Breakwaters for Shoreline Stabilization.* In Proceedings of Coastal Zone '85, pp. 1776-1795. American Society of Civil Engineers.	Chesapeake Bay	• reef-type breakwaters: low-crested rubble-mound breakwaters built parallel to the shoreline • revetments • bulkheads • groins
14	Tainter, S.P. 1982. *Bluff Slumping and Stability: A Consumer's Guide.* Michigan Sea Grant.	United States	• reshaping bluff face • subsurface drainage • surface water control • vegetation
15	FEMA. 1986. *Coastal Construction Manual.* Federal Emergency Management Agency, Washington, DC.	United States	• structural design recommendations • landscaping • dune protection • bulkheads • use of earthfill
16	Hardaway, C.S., and J.R. Gunn. 1991. *Headland Breakwaters in Chesapeake Bay.*	Chesapeake Bay	• headland breakwater systems: series of headlands and pocket beaches

(1) Determine the limits of the shoreline reach;

(2) Determine the rates and patterns of erosion and accretion and the active processes of erosion within the reach;

(3) 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;

(4) Determine the direction of sediment transport and, if possible, estimation of the magnitude of the gross and net sediment transport rates; and

(5) Estimate factors such as ground-water seepage or surface water runoff that contribute to erosion.

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, and 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 the transfer of wave energy, which can cause erosion 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 shore erosion control project.

Fixed engineering structures are built to protect upland areas when resources become impacted 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 shoreline as well. One example of accelerated erosion of unprotected properties adjacent to shoreline erosion structures is the Siletz Spit, Oregon, site (Komar and McDougal, 1988).

For sites where soil bioengineering marsh creation would not be an effective means of streambank or shoreline stabilization, a variety of engineering approaches can be considered. One approach involves the design and installation of fixed engineering structures. Bulkheads and seawalls are two types of wave-resistant walls that are similar in design but slightly different in purpose. Bulkheads are primarily soil-retaining structures designed also to resist wave attack (Figure 6-19). 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 (Baechler et al., 1970; Arsenault, 1975). 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, which have some value as nutrients in the marine environment but are toxic above trace levels (Weis et al., 1991; Weis et al., 1992).

A revetment is another 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 (Figure 6-20). 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 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).

Groins are structures that are built perpendicular to the shore and extend into the water. Groins 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.

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, such as the one shown in Figure 6-17,

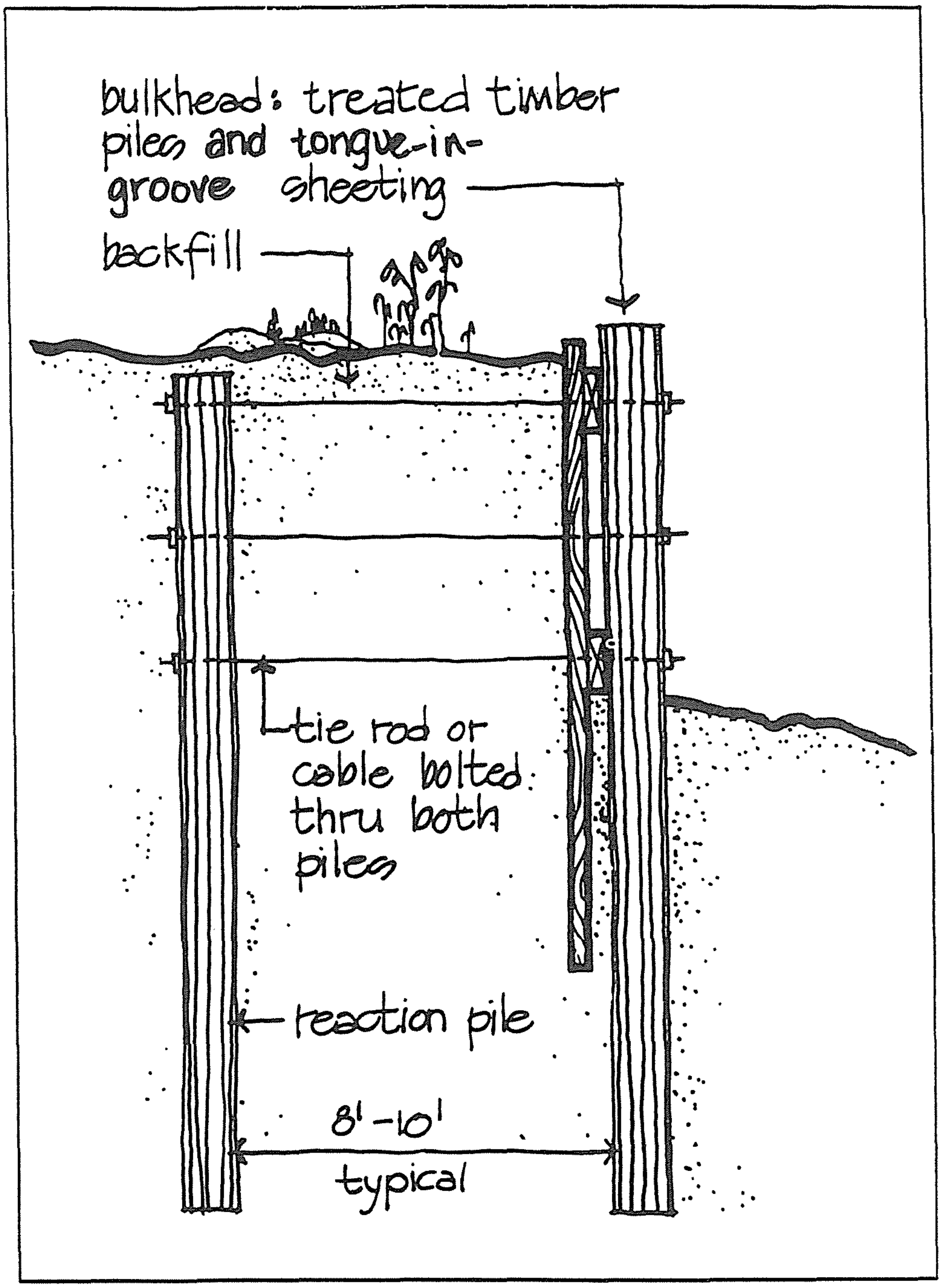


Figure 6-19. Schematic cross section of a timber bulkhead showing important design elements (FEMA, 1986).

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).

Selection of Structural Stabilization Techniques

Five factors are typically taken into consideration when choosing from among the various alternatives of engineering practices for protection of eroding shorelines (USACE, 1984):

(1) Foundation conditions;
(2) Level of exposure to wave action;
(3) Availability of materials;
(4) Initial costs and repair costs; and
(5) 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 coastal 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

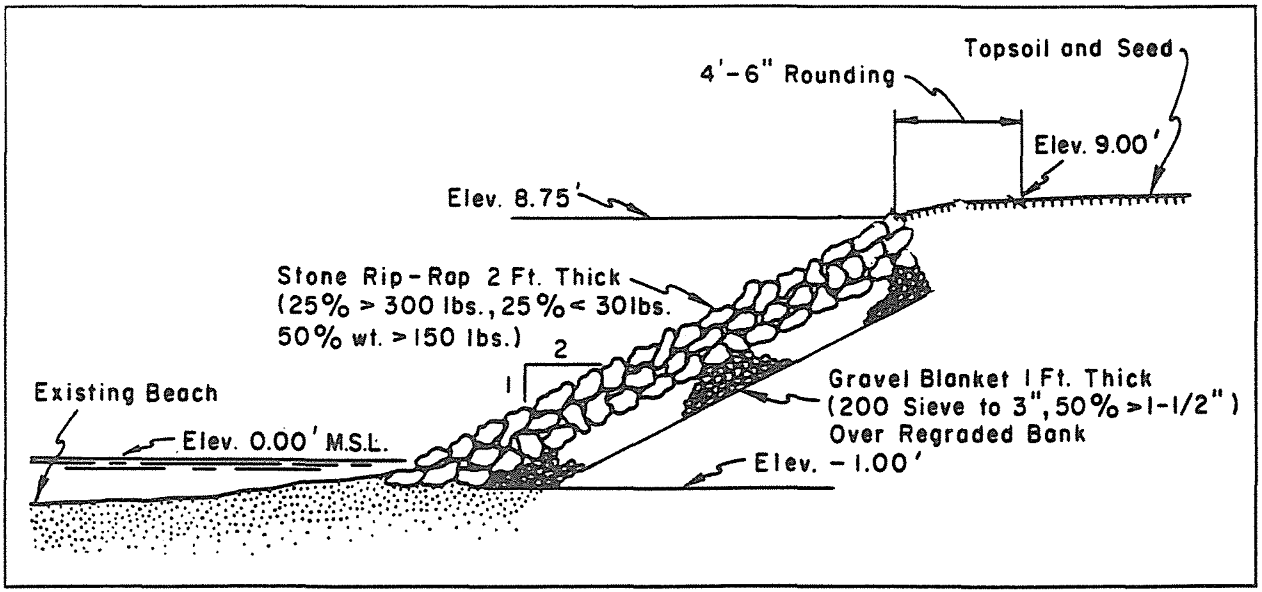


Figure 6-20. Schematic cross section of a stone revetment showing important design elements (USACE, 1984).

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 are influenced not only by the availability of materials but also by the type of structure that is selected for protection of the shoreline. The total cost of a shoreline or streambank protection project should be viewed as including both the initial costs of materials and the annual costs of maintenance. 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).

Other engineering practices for stabilizing shorelines and streambanks rely less on fixed structures. 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 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).

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 (Thompson, 1973). Removal of substantial amounts of bottom sediments in coastal areas can disrupt populations of fish, shellfish, and benthic organisms. 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. Fill materials should also be analyzed for the presence of contaminants, and contaminated sediment should not be used. Turbidity levels in the overlying waters can also be raised to undesirable levels (Sherk et al., 1976; O'Connor et al., 1976). Certain coastal areas may have seasonal restrictions on obtaining fill from nearby submerged coastal areas (Profiles Research and Consulting Group, Inc., 1980). 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.

■ *c. 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.*

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 (Figure 6-21). 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.

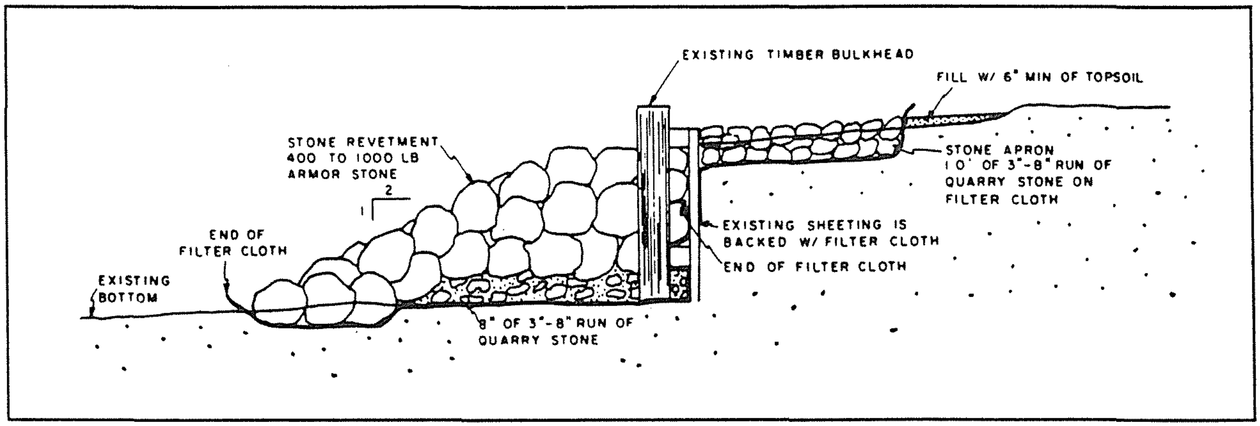


Figure 6-21. Schematic cross section of toe protection for a timber bulkhead showing important design elements (Maryland Department of Natural Resources, 1982).

Return Walls. 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 (Figure 6-22). 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.

Maintenance of Structures. Periodic maintenance of structures is necessary to repair the damage from storms and winter ice and to address the effects of flanking and off-shore profile deepening. The maintenance varies with the structural type, but annual inspections should be made by the property owners. 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.

▨ d. *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.*

Many streambank or shoreline protection projects result in a transfer of energy from one area to another, which causes increased erosion in the adjacent area (USACE, 1981a). Property owners should consider the possible effects of erosion control measures on other properties located along the shore.

▨ e. *Establish and enforce no-wake zones to reduce erosion potential from boat wakes.*

No-wake zones should be given preference over posted speed limits in shallow coastal waters for reducing the erosion potential of boat wakes on streambanks and shorelines. Posted speed limits on waterways generally restrict the movement of recreational boating traffic to speeds in the range of 6-8 knots, but motorboats traveling at these speeds in shallow waters can be expected to throw wakes whose wave heights will be at or near the maximum size that can be produced by the boats.

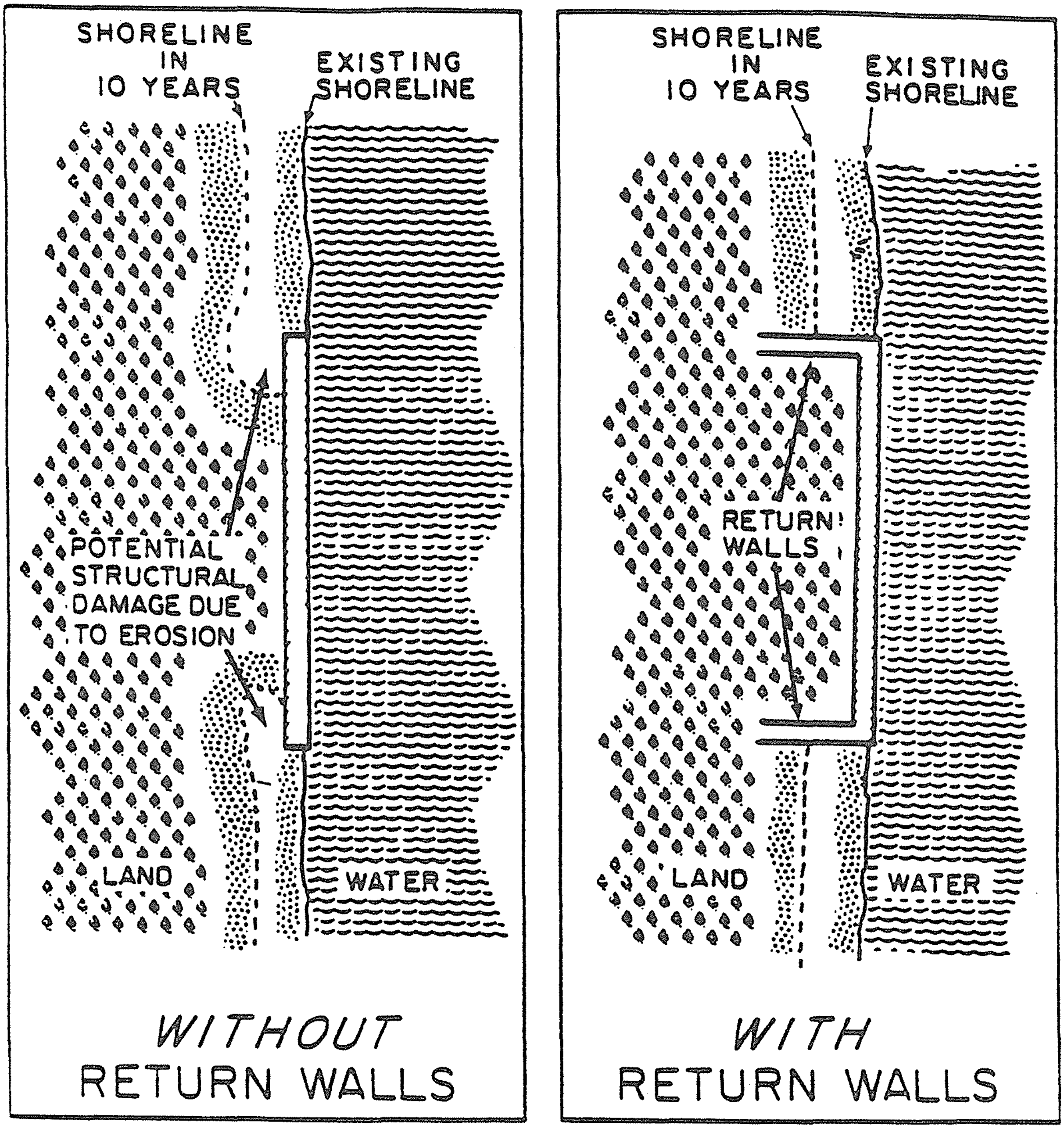


Figure 6-22. Example of return walls to prevent flanking in a bulkhead (Maryland Department of Natural Resources, 1982).

In theory, the boat speed that will produce the maximum wake depends on the depth of the water and the speed of the boat (Johnson, 1957). The ratio of these variables is called the Froude Number, named after an early scientific investigator of fluid mechanics. As the Froude Number (F) approaches 1, the wakes produced by a boat will reach their maximum value. The relationship between the Froude Number, the boat speed, and the basin depth is described by the following equation (Johnson, 1957):

$$F = V_s / \sqrt{gd}$$

where:

V_s = Velocity of boat speed (knots)
g = Gravity constant (ft/sec^2)
d = Basin depth (ft)

It is important to note that this equation can be used only to describe the boat speed at which a maximum wake will occur in water of a known depth. The equation cannot be used to calculate the actual height of the maximum wake.

Table 6-5 contains values for **F** calculated for different combinations of boat speed and water depth, prepared as part of a study of wakes produced by recreational boating traffic on the Chesapeake Bay in Maryland (Maryland Department of Natural Resources, 1980). The dotted line drawn through this table shows those combinations for which **F** approximately equals 1. For instance, boats traveling 6 to 8 knots can be expected to produce their maximum wake in water depths of 4 to 6 feet, while boats traveling 10 to 12 knots can be expected to produce their maximum wake in water depths of 12 feet. These depths are typical of conditions in small creeks and coves in coastal areas where there is generally the greatest concern about shore erosion resulting from recreational motorboat traffic.

Table 6-5 was verified with field data collected in a shallow creek in Maryland's Chesapeake Bay for two types of motorboats. The results are presented in Figure 6-23. As predicted from Table 6-5, maximum wake heights were produced at speeds ranging from 6 to 8 knots. Wake heights did not increase with increasing speed.

These results show that boats can be expected to still produce damaging wakes as they slow from high speed to enter a narrow creek or cove with a posted 6-knot limit. Locating the speed reduction zones in open water, so that boats are slowing through the critical range of velocities far from shore, would reduce the potential for shore erosion from boat wakes. The designation of no-wake zones, rather than posted speed limits, would also reduce the potential for shore erosion from boat wakes.

■ *f. 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).

A recent report, *Managing Coastal Erosion* (NRC, 1990), summarizes the experience of coastal States in the implementation and administration of regulatory setback programs. The NRC report also discusses "the taking issue," which views setbacks as a severe restriction on the rights of private landowners to fill or build in designated setback areas. Setback regulations implemented in some States have been challenged in the courts on the grounds of "the taking issue," i.e., that the setback requirements are so restrictive that they "take" the value of the property without providing compensation to the property owners, violating the Fifth Amendment to the U.S. Constitution. The courts, however, have provided general approval of floodplain and wetlands regulations, and the NRC report concludes: "there is a strong legal basis for the broader use of setbacks for coastal construction based on the best available scientific estimates of future erosion rates."

Table 6-5. Froude Number for Combinations of Water Depth and Boat Speed (Maryland Department of Natural Resources, 1980)

DEPTH (ft)	SPEED (Knots)								
	2	4	6	8	10	12	14	16	18
2	0.42	0.83	1.25	1.66	2.08	2.49	2.91	3.32	3.74
4	0.29	0.59	0.88	1.17	1.47	1.76	2.06	2.35	2.64
6	0.24	0.48	0.72	0.96	1.20	1.44	1.68	1.92	2.16
8	0.21	0.42	0.62	0.83	1.04	1.25	1.45	1.66	1.87
10	0.18	0.37	0.56	0.74	0.93	1.11	1.30	1.49	1.67
12	0.17	0.34	0.51	0.68	0.85	1.02	1.19	1.36	1.52
14	0.16	0.31	0.47	0.63	0.78	0.94	1.10	1.26	1.41
16	0.15	0.29	0.44	0.59	0.73	0.88	1.03	1.17	1.32
18	0.14	0.28	0.42	0.55	0.69	0.83	0.97	1.11	1.25

Table 6-6 contains a summary of State programs and experiences with setbacks. 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; and
- 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. These effects are described and discussed in Chapter 4 of this guidance document. 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,

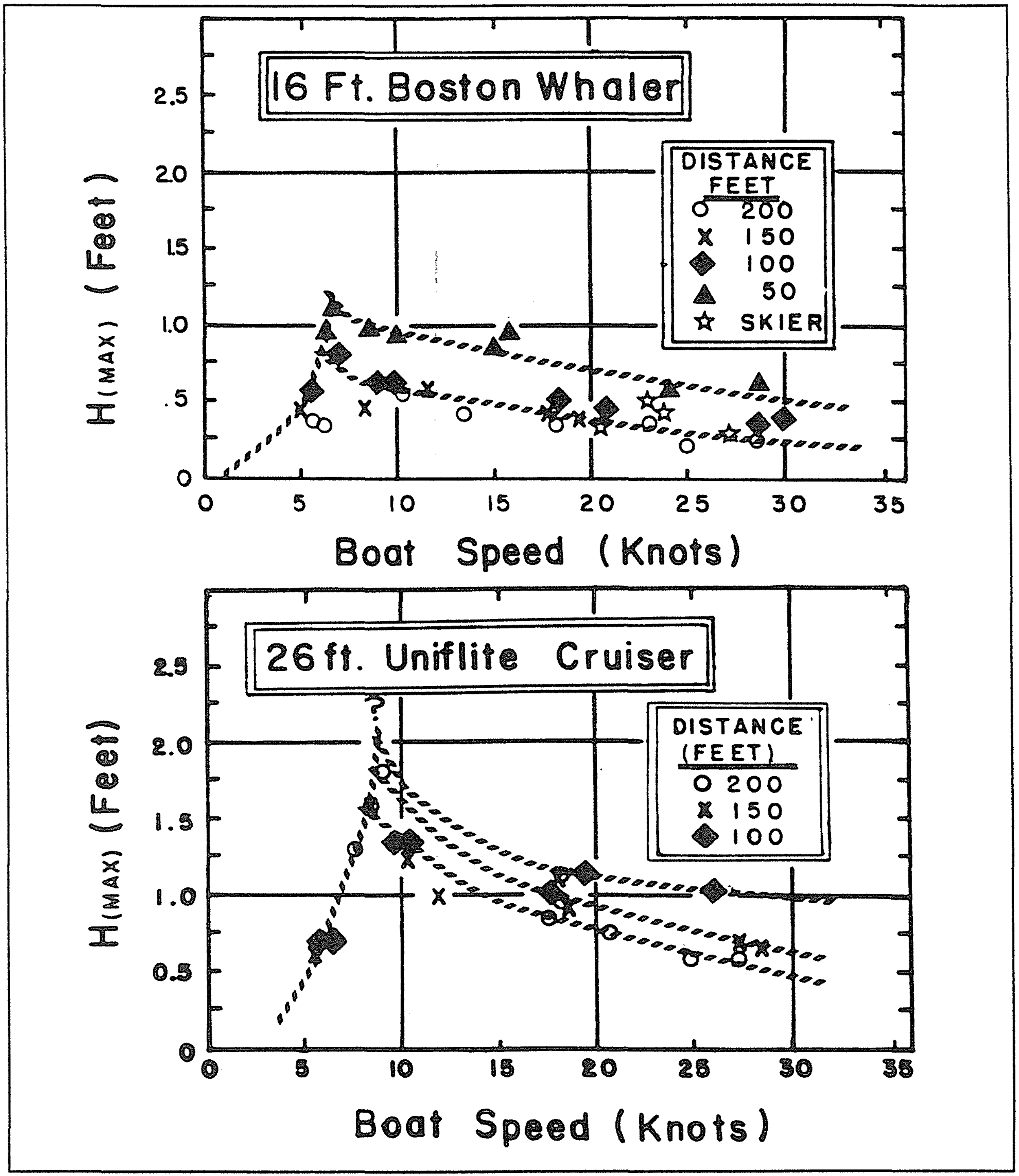


Figure 6-23. Wakes from two different types of boat hulls (Maryland Department of Natural Resources, 1980).

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. This approach also helps 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.

Table 6-6. Examples of State Programs Defining Minimum Set-Backs (National Research Council, 1990)

State/Territory	Recession Rates from Aerial Photos	Recession Rates from Charts	Recession Rates from Ground Surveys	Erosion Setbacks Established[a]	Reference Feature	Years of Setback	Local Administration	One Foot per Year Standard	Fixed Setback	Floating Setback
Alabama	Y	Y	N	Y	MHW	NA	N	Y	N	
Alaska	Y	Y		N	NA	NA	NA	NA	NA	NA
American Samoa	N	N	N	N	NA	NA	NA	NA	NA	NA
California	Y	Y	Y	N	NA	NA	Y	NA	NA	NA
Connecticut	Y	Y		N	NA	NA	NA	NA	NA	NA
Delaware	Y	Y		Y4	TD	NA	Y	N	Y	N
Florida	Y	Y		Y5	NA	30	Y	N	Y	N
Georgia	Y	Y		N	NA	NA	NA	NA	NA	NA
Hawaii	N	N	N	Y	6	N	Y	N	Y	N
Indiana	Y	N	Y	N	NA	NA	NA	Y	NA	NA
Illinois	Y	Y	Y	N	NA	NA	NA		NA	NA
Louisiana	Y	Y	N	N	NA	NA	NA	NA	NA	NA
Maine	N	N	Y	N7	NA	NA	NA	NA	NA	NA
Maryland	Y	Y		N	NA	NA	NA	NA	NA	NA
Massachusetts	Y	Y	N	N	NA	NA	NA	NA	NA	NA
Michigan	Y	N	N	Y	BC2	30	Y	Y	N	Y
Minnesota	Y	N	N	N	NA	NA	NA	Y	NA	NA
Mississippi	N	N	N	N	NA	NA	NA	NA	NA	NA
New Hampshire	N	N	N	N	NA	NA	NA	NA	NA	NA
New Jersey	Y	Y	Y	Y	MHW	50				
New York	Y	Y	N	Y	BC	30-40	Y	Y	Y	N
North Carolina	Y	N		Y	DC	30-60	Y	N	N	Y
N. Mariana's	N	N	N	N	NA	NA	NA	NA	NA	NA
Ohio	Y	Y	N	N1	BC	30	NA	Y	Y	N
Oregon				N		NA	NA	NA	NA	NA
Pennsylvania	Y	N	Y	Y	BC	50+	Y	Y	N	Y
Puerto Rico	N	N	N	N	NA	NA	NA	NA		
Rhode Island	N	N	Y	Y	DC	30	N	N7	Y	N
South Carolina			Y	Y		40	BL		Y	N
Texas	Y	Y	Y	N	NA	NA	NA	NA	NA	NA
Virgin Islands	N	N	N	N	NA	NA	NA	NA	NA	NA
Virginia	Y	Y		N	MHW	NA	Y			
Washington				N	NA	NA	NA	NA	NA	NA
Wisconsin	Y	Y	N	N3	NA	NA	NA		N	Y

Note: 1 = setbacks may be established within 2 years; 2 = bluff crest or edge of active erosion; 3 = some counties have setbacks; 4 = has 100-foot setback regulation over new subdivisions and parcels where sufficient room exists landward of setback; 5 = not all counties have coastal construction control lines established; 6 = storm debris line or vegetation line; 7 = 2 feet per year standard. Y, yes; N, no; NA, not applicable; BC, bluff crest; MHW, mean high water; TD, toe of dune; DC, dune crest, toe of frontal dune or vegetation line; BL, base line. A blank means no information was available.

[a] Most States have setbacks from water line but not based on an erosion hazard.

Almost all States with setback regulations have modified their original programs to improve effectiveness or correct unforeseen problems (NRC, 1990). States' 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, the approach that best designates coastal 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 as a result of global warming. 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.

5. Costs for All Practices

This section describes costs for representative activities that would be undertaken in support of one or more of the practices listed under this management measure. The description of the costs is grouped into the following three categories: (1) costs for streambank and shoreline stabilization with vegetation; (2) costs for streambank and shoreline stabilization with engineering structures; and (3) costs for designation and enforcement of boating speed limits.

a. Vegetative Stabilization for Shorelines and Streambanks

Representative costs for this practice can include costs for wetland plants and riparian area vegetation, including trees and shrubs. Additional costs could be incurred depending on the level of site preparation that is required. The items of work could include (1) clearing the site of fallen trees and debris; (2) extensive site work requiring heavy construction equipment; (3) application of seed stock or sprigging of nursery-reared plants; (4) application of fertilizer (most typically for marsh creation); and (5) postproject maintenance and monitoring. For a more extensive description of these tasks, refer to the sections of Chapter 7 describing marsh restoration efforts.

(1) Costs reported in 1989 for bottomland forest plants using direct seeding were \$40 to \$60 per acre (NRC, 1991). If vegetation is assumed to be planted across a 50-foot width along the shoreline or streambank, the cost per linear foot of shore or streambank, in 1990 dollars, can be calculated as \$0.05 - \$0.08/foot.

(2) Costs reported in 1990 for nursery-reared tree seedlings were \$212.50 per acre (Illinois Department of Conservation, 1990). If vegetation is assumed to be planted across a 50-foot width along the shoreline or streambank, the costs per linear foot of shore or streambank, in 1990 dollars, can be calculated as \$0.25/foot.

(3) Costs reported for restoration of riparian areas in Utah between 1985 and 1988 included extensive site work: bank grading, installation of riprap and sediment traps in deep gullies, planting of juniper trees and willows, and fencing to protect the sites from intrusion by livestock. Assuming a 100-foot width along the shore or streambank for this work, the reported costs, in 1990 dollars, of \$2,527 per acre can be calculated as \$5.94 per foot.

(4) Costs were reported in 1988 for vegetative erosion control projects involving creation of tidal fringe marsh, using nursery-reared *Spartina alterniflora* and *S. patens* along the shorelines of the Chesapeake

Bay in Maryland (Maryland Eastern Shore Resource Conservation and Development Area). Two projects involving marsh creation along a total of 4,650 linear feet of shoreline averaged $20.48 per foot. Costs of 12 projects involving marsh creation combined with grading and seeding of the shoreline bank ranging in height from 5 to 12 feet averaged $54.82 per foot along a total of 8,465 feet. These costs can be calculated in 1990 dollars as:

Marsh creation - no bank grading	$21.44 per foot
Marsh creation - bank grading	$57.40 per foot

b. Structural Stabilization for Shorelines and Streambanks

Representative costs for structural stabilization typically include costs for survey and design and for extensive site work, including costs to gain access for trucks and front-end loaders necessary to place the stone (for revetments) or sheet pile (for bulkheads). As indicated in the data described below for specific projects, costs frequently vary depending on the level of wave exposure at the site and on the overall length of shoreline or streambank that is being protected in a single project. In some of the examples shown below, construction costs were reported along with design and administration costs. For cases where only installation costs were reported in the source document, a total project cost was computed by adding 15 percent of first construction costs to the reported installation cost, and then dividing by the reported project length to compute cost per foot. Thus, all costs shown below include design and administration costs.

(1) Costs for timber bulkhead on private property along 100 linear feet of shore on Cabin Creek, York County, Virginia (less than 2 miles of wave exposure), in 1990 dollars, were $69 per foot (Virginia Department of Conservation and Recreation, undated).

(2) Costs for replacement of timber bulkhead on private property along 375 linear feet of shore on the Rappahannock River, Middlesex County, Virginia (2 to 5 miles of wave exposure), in 1990 dollars, were $60 per foot (Virginia Department of Conservation and Recreation, undated).

(3) Costs for timber bulkhead at Whidbey Island Naval Air Station, Oak Harbor, Washington (more than 5 miles of wave exposure), in 1990 dollars, were $129 per foot (USACE, 1981a).

(4) Costs for timber and steel bulkhead along 200 feet of shoreline of a County park at Port Wing, Bayfield County, Wisconsin (more than 5 miles of exposure), in 1990 dollars, were $356 per foot (USACE, 1981a).

(5) Costs for stone revetment on private property along 270 feet of shoreline on Linkhorn Bay, Virginia Beach, Virginia (less than 2 miles of wave exposure), in 1990 dollars, were $63 per foot (Virginia Department of Conservation and Recreation, undated).

(6) Costs for stone revetment and bank grading along 420 linear feet of shoreline on James River, Surry County, Virginia (2 to 5 miles of exposure), in 1990 dollars, were $342 per foot (Virginia Department of Conservation and Recreation, undated).

(7) Costs for stone revetment on private community property along 2000 linear feet of shoreline on Lorain Harbor, Ohio (more than 5 miles of exposure), in 1990 dollars, were $1,093 per foot (USACE, 1981b).

(8) Costs for beachfill and dune construction on a city public beach along 10,000 feet of shoreline at North Nantasket Beach, Hull, Massachusetts (more than 5 miles of exposure), in 1990 dollars, were $162 per foot (USACE, 1988).

(9) Costs for six riprap and six gabion breakwaters with beachfill on State Wildlife Management Area property along 1250 linear feet of shore on the James River, Surry County, Virginia (2 to 5 miles of exposure), in 1990 dollars, were $62 per foot (Hardaway et al., 1991).

(10) Costs for breakwaters, beachfill, and beachgrass planting at a County park along 1100 feet of shoreline at Elm's Beach, Chesapeake Bay, Maryland (more than 5 miles of exposure), in 1990 dollars, were $292 per foot (Hardaway and Gunn, 1991).

(11) Costs for breakwaters, beachfill, and revetment along 11,000 feet of shoreline at Maumee Bay State Park, Ohio (more than 5 miles of exposure), in 1990 dollars, were $961 per foot (USACE, 1982).

c. Designation and Enforcement of Boating Speed Limits

Representative costs for this practice can be broken down into the following two tasks:

(1) Providing notification of a posted speed limit or "no-wake" zone in navigational channels along coastal waterways. One approach used to advise boaters of posted speed limits is the placement of marked buoys along the channel in speed reduction zones. Alternatively, signs designating speed reduction zones can be placed on pilings that are driven into the bottom of the coastal creek or bay. In narrow creeks or coves, signs can be mounted onshore along the streambank. The number of signs, buoys, or beacons that will be required will depend on the length and configuration of the channel. For a channel 1 mile in length that is fairly straight and linear, with good visibility on both the downstream and upstream approaches, three posted speed limit signs could be deployed for upstream traffic and three for downstream traffic. Representative costs for this practice, in 1990 dollars, can be estimated from data provided by the Maryland Department of Natural Resources Marine Police Administration. These costs include all labor, materials, and installation:

(a) Costs for purchasing, marking, and setting six buoys at $285 each are $1,710.

(b) Costs for six onshore signs mounted on 2-ft by 3-ft by 8-ft posts at $165 each are $990.

(c) Costs for six channel beacons mounted on offshore 4-ft by 4-ft by 42-ft pilings at $1,850 each are $11,100.

(2) The enforcement of designated boating speed limit zones, which can be expected to include costs for the acquisition and maintenance of marine police vessels and costs for marine police personnel to monitor boating patterns. Representative costs, in 1990 dollars, which are incurred for these items by the Maryland Department of Natural Resources (Gwynne Schultz, personal communication, 199~~2) are~~ listed below:

(a) One large patrol boat (suitable for areas of open water in coastal bays or rivers):

Acquisition	$180,000
Annual maintenance per vessel per year	$ 2,000
Crew of three marine police	$ 90,000

(b) One small patrol boat (suitable for protected creeks and coves):

Acquisition	$20,000
Annual maintenance per vessel per year	$ 2,000
Crew of two marine police	$60,000

These costs do not consider overtime that is provided to members of the Maryland Marine Police for any shift greater than 8 hours in length. No overtime is paid for holidays.

V. GLOSSARY

Accretion: May be either *natural* or *artificial*. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of waterborne or airborne material. Artificial accretion is a similar buildup of land by reason of an act of humans, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means. Also known as aggradation. (USACE, 1984)

Alongshore: Parallel to and near the shoreline; *longshore* (USACE, 1984).

Armor unit: A relatively large quarrystone or concrete shape that is selected to fit specified geometric characteristics and density. Armor units are usually uniform in size and usually large enough to require individual placement. In normal cases armor units are used as primary wave protection and are placed in thicknesses of at least two units. (USACE, 1984)

Artificial nourishment: The process of replenishing a beach with material (usually sand) obtained from another location (USACE, 1984).

Backshore: That zone of the shore or beach lying between the foreshore and the coastline comprising the *berm* or *berms* and acted upon by waves only during severe storms, especially when combined with exceptionally high water (USACE, 1984).

Bank: (1) The rising ground bordering a lake, river, or sea; or of a river or channel, for which it is designated as right or left as the observer is facing downstream. (2) An elevation of the sea floor or large area, located on a continental (or island) shelf and over which the depth is relatively shallow but sufficient for safe surface navigation; a group of shoals. (3) In its secondary sense, used only with a qualifying word such as "sandbank" or "gravelbank," a shallow area consisting of shifting forms of silt, sand, mud, and gravel. (USACE, 1984)

Bar: A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents (USACE, 1984).

Barrier beach: A bar essentially parallel to the shore, the crest of which is above normal high water level (USACE, 1984).

Basin, boat: A naturally or artificially enclosed or nearly enclosed harbor area for small craft (USACE, 1984).

Bathymetry: The measurement of depths of water in oceans, seas, and lakes; also information derived from such measurements (USACE, 1984).

Bay: A recess in the shore or an inlet of a sea between two capes or headlands, not so large as a gulf but larger than a cove (USACE, 1984).

Bayou: A minor sluggish waterway or estuarine creek, tributary to, or connecting, other stream or bodies of water, whose course is usually through lowlands or swamps (USACE, 1984).

Beach: The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach—unless otherwise specified—is the mean low water line. A beach includes *foreshore* and *backshore*. See also *shore*. (USACE, 1984)

Beach planting: The placement of vegetation in the zone of sedimentary material that extends landward from the low water line to the place where there is marked change in material or form, or to the line of permanent vegetation.

Beach accretion: See *accretion* (USACE, 1984).

Beach berm: A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms; others have one or several. (USACE, 1984)

Beach erosion: The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind (USACE, 1984).

Beach face: The section of the beach normally exposed to the action of the wave uprush. The *foreshore* of a *beach* (not synonymous with *shoreface*). (USACE, 1984)

Beach fill: Material placed on a beach to renourish eroding shores (USACE, 1984).

Beach width: The horizontal dimension of the beach measured normal to the shoreline (USACE, 1984).

Bench mark: A permanently fixed point of known elevation. A primary bench mark is one close to a tide station to which the tide staff and tidal datum originally are referenced. (USACE, 1984)

Bluff: A high, steep bank or cliff (USACE, 1984).

Bottom: The ground or bed under any body of water; the bottom of the sea (USACE, 1984).

Bottom (nature of): The composition or character of the bed of an ocean or other body of water (e.g., clay, coral, gravel, mud, ooze, pebbles, rock, shell, shingle, hard, or soft) (USACE, 1984).

Boulder: A rounded rock more than 10 inches in diameter; larger than a cobblestone. See *soil classification*. (USACE, 1984)

Breakwater: A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action. (USACE, 1984)

Bulkhead: A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action. (USACE, 1984)

Bypassing, sand: Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may include natural movement as well as movement caused by humans. (USACE, 1984)

Canal: An artificial watercourse cut through a land area for such uses as navigation and irrigation (USACE, 1984).

Cape: A relatively extensive land area jutting seaward from a continent or large island that prominently marks a change in, or interrupts notably, the coastal trend; a prominent feature (USACE, 1984).

Channel: (1) A natural or artificial waterway or perceptible extent that either periodically or continuously contains moving water, or that forms a connecting link between two bodies of water. (2) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation. (3) A large strait, as the English Channel. (4) The deepest part of a stream, bay, or strait through which the main volume or current of water flows. (USACE, 1984)

Channelization and channel modification: River and stream channel engineering for the purpose of flood control, navigation, drainage improvement, and reduction of channel migration potential; activities include the straightening, widening, deepening, or relocation of existing stream channels, clearing or snagging operations, the excavation of borrow pits, underwater mining, and other practices that change the depth, width, or location of waterways or embayments in coastal areas.

Clay: See *soil classification* (USACE, 1984).

Cliff: A high, steep face of rock; a precipice (USACE, 1984).

Coast: A strip of land of indefinite width (may be several kilometers) that extends from the shoreline inland to the first major change in terrain features (USACE, 1984).

Coastal area: The land and sea area bordering the shoreline (USACE, 1984).

Coastal plain: The plain composed of horizontal or gently sloping strata of clastic materials fronting the coast, and generally representing a strip of sea bottom that has emerged from the sea in recent geologic time (USACE, 1984).

Coastline: (1) Technically, the line that forms the boundary between the *coast* and the *shore*. (2) Commonly, the line that forms the boundary between the land and the water. (USACE, 1984)

Cobble (cobblestone): See *soil classification* (USACE, 1984).

Continental shelf: The zone bordering a continent and extending from the low water line to the depth (usually about 180 meters) where there is a marked or rather steep descent toward a greater depth.

Contour: A line on a map or chart representing points of equal elevation with relation to a datum. It is called an isobath when it connects points of equal depth below a datum. Also called depth contour. (USACE, 1984)

Controlling depth: The least depth in the navigable parts of a waterway, governing the maximum draft of vessels that can enter (USACE, 1984).

Convergence: (1) In refraction phenomena, the decreasing of the distance between orthogonals in the direction of wave travel. Denotes an area of increasing wave height and energy concentration. (2) In wind-setup phenomena, the increase in setup observed over that which would occur in an equivalent rectangular basin of uniform depth, caused by changes in plainform or depth; also the decrease in basin width or depth causing such an increase in setup (USACE, 1984).

Cove: A small, sheltered recess in a coast, often inside a larger embayment. (USACE, 1984)

Current: A flow of water (USACE, 1984).

Current, coastal: One of the offshore currents flowing generally parallel to the shoreline in the deeper water beyond and near the surf zone. Such currents are not related genetically to waves and resulting surf, but may be related to tides, winds, or distribution of mass. (USACE, 1984)

Current, drift: A broad, shallow, slow-moving ocean or lake current. Opposite of *current, stream*. (USACE, 1984)

Current, ebb: The tidal current away from shore or down a tidal stream. Usually associated with the decrease in the height of the tide. (USACE, 1984)

Current, flood: The tidal current toward shore or up a tidal stream. Usually associated with the increase in the height of the tide. (USACE, 1984)

Current, littoral: Any current in the littoral zone caused primarily by wave action; e.g., longshore current, rip current. See also *current, nearshore*. (USACE, 1984)

Current, longshore: The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline (USACE, 1984).

Current, nearshore: A current in the *nearshore zone* (USACE, 1984).

Current, offshore: See *offshore current* (USACE, 1984).

Current, tidal: The alternating horizontal movement of water associated with the rise and fall of the tide caused by the astronomical tide-producing forces. Also *current, periodic*. See also *current, flood* and *current, ebb*. (USACE, 1984)

Cutoff: Wall, collar, or other structure, such as a trench, filled with relatively impervious material intended to reduce seepage of water through porous strata; in river hydraulics, the new and shorter channel formed either naturally or artificially when a stream cuts through the neck of a band.

Deep water: Water so deep that surface waves are little affected by the ocean bottom. Generally, water deeper than one-half the surface wavelength is considered deep water. Compare *shallow water*. (USACE, 1984)

Delta: An alluvial deposit, roughly triangular or digitate in shape, formed at a river mouth (USACE, 1984).

Depth: The vertical distance from a specified tidal datum to the sea floor (USACE, 1984).

Depth of breaking: The still-water depth at the point where the wave breaks (USACE, 1984).

Detritus: Loose material worn or broken away from a mass, as by the action of water, usually carried from inland sources by streams (USACE, 1981a).

Dike (dyke): A channel stabilization structure sited in a river or stream perpendicular to the bank.

Downdrift: The direction of predominant movement of littoral materials (USACE, 1984).

Drift (noun): (1) Sometimes used as a short form for *littoral drift*. (2) The speed at which a current runs. (3) Floating material deposited on a beach (driftwood). (4) A deposit of a continental ice sheet; e.g., a drumlin. (USACE, 1984)

Dunes: (1) Ridges or mounds of loose, wind-blown material, usually sand. (2) Bed forms smaller than bars but larger than ripples that are out of phase with any water-surface gravity waves associated with them (USACE, 1984).

Ebb tide: The period of tide between high water and the succeeding low water; a falling tide (USACE, 1984).

Embankment: An artificial bank such as a mound or dike, generally built to hold back water or to carry a roadway (USACE, 1984).

Embayment: An indentation in the shoreline forming an open bay (USACE, 1984).

Ephemeral: Lasting for a brief time; short-lived; transitory (Morris, 1978).

Erosion: The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation (USACE, 1984).

Estuary: (1) The part of the river that is affected by tides. (2) The region near a river mouth in which the fresh water in the river mixes with the salt water of the sea (USACE, 1984).

Eutrophication: The alteration of lake ecology through excessive nutrient input, characterized by excessive growth of aquatic plants and algae and low levels of dissolved oxygen (USEPA, 1992).

Fastland: Land near the shoreline that is safely above the erosive zone of waves and tides. The area landward of the bank.

Fetch: The area in which seas are generated by a wind having a fairly constant direction and speed. Sometimes used synonymously with fetch length (USACE, 1984).

Flood tide: The period of tide between low water and the succeeding high water; a rising tide (USACE, 1984).

Flow alteration: A category of hydromodification activities that results in either an increase or a decrease in the usual supply of fresh water to a stream, river, or estuary.

Foreshore: The part of the shore, lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low-water mark, that is ordinarily traversed by the uprush and back rush of the waves as the tides rise and fall. See *beach face.* (USACE, 1984)

Freeboard: The additional height of a structure above design high-water level to prevent overflow. Also, at a given time, the vertical distance between the water level and the top of the structure. On a ship, the distance from the waterline to main deck or gunwale (USACE, 1984).

Froude number: The dimensionless ratio of the inertial force to the force of gravity for a given fluid flow. It may be given as $Fr = V/Lg$,where V is a characteristic velocity, L is a characteristic length, and g the acceleration of gravity—or as the square root of this number. (USACE, 1984)

Gabion: A rectangular basket or mattress made of galvanized, and sometimes PVC-coated, steel wire in a hexagonal mesh. Gabions are generally subdivided into equal-sized cells that are wired together and filled with 4- to 8-inch-diameter stone, forming a large, heavy mass that can be used as a shore-protection device. (USACE, 1990)

Generation of waves: (1) The creation of waves by natural or mechanical means. (2) The creation and growth of waves caused by a wind blowing over a water surface for a certain period of time (USACE, 1984).

Geomorphology: That branch of both physiography and geology that deals with the form of the Earth, the general configuration of its surface, and the changes that take place in the evolution of landform (USACE, 1984).

Grade stabilization structure: A structure used to control the grade and head cutting in natural or artificial channels (USDA-SCS, 1988).

Gradient (grade): See *slope.* With reference to winds or currents, the rate of increase or decrease in speed, usually in the vertical; or the curve that represents this rate (USACE, 1984).

Gravel: See *soil classification* (USACE, 1984).

Groin: A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore (USACE, 1984).

Groin system: A series of groins acting together to protect a section of beach. Commonly called a groin field. (USACE, 1984)

Ground water: Subsurface water occupying the zone of saturation. In a strict sense, the term is applied only to water below the water table (USACE, 1984).

Habitat: The place where an organism naturally lives or grows.

Harbor: Any protected water area affording a place of safety for vessels. See also *port.* (USACE, 1984)

Headland breakwater: A shore-connected breakwater (USACE, 1990).

Headland (head): A high, steep-faced promontory extending into the sea (USACE, 1984).

Height of wave: See *wave height* (USACE, 1984).

High tide, high water: The maximum elevation reached by each rising tide (USACE, 1984).

High water line: The intersection of the plane of mean high water with the shore. The shoreline delineated on the nautical charts of the National Ocean Service is an approximation of the high water line. For specific occurrences, the highest elevation on the shore reached during a storm or rising tide, including meteorological effects (USACE, 1984).

Hurricane: An intense tropical cyclone in which winds tend to spiral inward toward a core of low pressure, with maximum surface wind velocities that equal or exceed 33.5 meters per second (75 mph or 65 knots) for several minutes or longer at some points. *Tropical storm* is the term applied if maximum winds are less than 33.5 meters per second. (USACE, 1984)

Hydrography: (1) A configuration of an underwater surface including its relief, bottom materials, coastal structures, etc. (2) The description and study of seas, lakes, rivers, and other waters (USACE, 1984).

Hydrologic modification: The alteration of the natural circulation or distribution of water by the placement of structures or other activities (USEPA, 1992).

Hydromodification: Alteration of the hydrologic characteristics of coastal and noncoastal waters, which in turn could cause degradation of water resources.

Impoundment: The collection and confinement of water as in a reservoir or dam.

Inlet: (1) A short, narrow waterway connecting a bay, lagoon, or similar body of water with a large parent body of water. (2) An arm of the sea (or other body of water) that is long compared to its width and may extend a considerable distance inland. See also *tidal inlet*. (USACE, 1984)

Inshore (zone): In beach terminology, the zone of variable width extending from the low water line through the breaker zone. See also *shoreface*. (USACE, 1984)

Jetty: (United States usage) On open seacoasts, a structure extending into a body of water, which is designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help deepen and stabilize a channel. (USACE, 1984)

Lagoon: A shallow body of water, like a pond or lake, usually connected to the sea (USACE, 1984).

Levee: An embankment or shaped mound for flood control or hurricane protection (USACE, 1981a).

Littoral: Of or pertaining to a shore, especially of the sea (USACE, 1984).

Littoral current: See *current, littoral* (USACE, 1984).

Littoral drift: The sedimentary material moved in the littoral zone under the influence of waves and currents (USACE, 1984).

Littoral transport: The movement of littoral drift in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (on-offshore transport) to the shore (USACE, 1984).

Littoral zone: In beach terminology, an indefinite zone extending seaward from the shoreline to just beyond the breaker zone (USACE, 1984).

Load: The quantity of sediment transported by a current. It includes the suspended load of small particles and the bedload of large particles that move along the bottom. (USACE, 1984)

Longshore: Parallel to and near the shoreline; *alongshore* (USACE, 1984).

Longshore current: See *current, longshore.*

Longshore transport rate: Rate of transport of sedimentary material parallel to the shore. Usually expressed in cubic meters (cubic yards) per year. Commonly synonymous with *littoral transport rate.* (USACE, 1984)

Low tide, low water: The minimum elevation reached by each falling tide. See *tide.* (USACE, 1984)

Low water datum: An approximation to the plane of mean low water that has been adopted as a standard reference plane (USACE, 1984).

Mangrove: A tropical tree with interlacing prop roots, confined to low-lying brackish areas (USACE, 1984).

Marsh: An area of soft, wet, or periodically inundated land, generally treeless and usually characterized by grasses and other low growth (USACE, 1984).

Marsh, salt: A marsh periodically flooded by salt water (USACE, 1984).

Marsh vegetation: Plants that grow naturally in a marsh.

Mean high water: The average height of the high waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce the results to the equivalent of a mean 19-year value. All low-water heights are included in the average where the type of field is either semidiurnal or mixed. Only lower-low water heights are included in the average where the type of tide is diurnal. So determined, mean low water in the latter case is the same as mean lower low water.

Mean sea level: The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings. Not necessarily equal to *mean tide level.* (USACE, 1984)

Mean tide level: A plane midway between *mean high water* and *mean low water.* Not necessarily equal to *mean sea level.* (USACE, 1984)

Meander: A bend in a river.

Mud: A fluid-to-plastic mixture of finely divided particles of solid material and water (USACE, 1984).

Nearshore (zone): In beach terminology an indefinite zone extending seaward from the shoreline well beyond the breaker zone. It defines the area of *nearshore currents.* (USACE, 1984)

Nearshore current system: The current system that is caused primarily by wave action in and near the breaker zone and consists of four parts: the shoreward mass transport of water; longshore currents; the seaward return flow, including rip currents; and the longshore movement of the expanding heads of rip currents (USACE, 1984).

Nourishment: The process of replenishing a beach. It may be brought about naturally by longshore transport or artificially by the deposition of dredged materials. (USACE, 1984)

Oceanography: The study of the sea, embracing and indicating all knowledge pertaining to the sea's physical boundaries, the chemistry and physics of seawater, and marine biology (USACE, 1984).

Offshore: (1) In beach terminology, the comparatively flat zone of variable width, extending from the breaker zone to the seaward edge of the Continental Shelf. (2) A direction seaward from the shore. (USACE, 1984)

Offshore current: (1) Any current in the offshore zone. (2) Any current flowing away from shore. (USACE, 1984)

Onshore: A direction landward from the sea (USACE, 1984).

Overtopping: Passing of water over the top of a structure as a result of wave runup or surge action (USACE, 1984).

Overwash: That portion of the uprush that carries over the crest of a berm or of a structure (USACE, 1984).

Oxbow: An isolated lake formed by a bend in a river that becomes disconnected from the river channel.

Parapet: A low wall built along the edge of a structure such as a seawall or quay (USACE, 1984).

Peninsula: An elongated body of land nearly surrounded by water and connected to a large body of land (USACE, 1984).

Percolation: The process by which water flows through the interstices of a sediment. Specifically, in wave phenomena, the process by which wave action forces water through the interstices of the bottom sediment and which tends to reduce wave heights. (USACE, 1984)

Pier: A structure, usually of open construction, extending out into the water from the shore, to serve as a landing place, recreational facility, etc., rather than to afford coastal protection. In the Great Lakes, a term sometimes improperly applied to jetties. (USACE, 1984)

Pile: A long, heavy timber or section of concrete or metal to be driven or jetted into the earth or seabed to serve as a support or protection (USACE, 1984).

Pile, sheet: A pile with a generally slender flat cross section to be driven into the ground or seabed and meshed or interlocked with like members to form a diaphragm, wall, or bulkhead (USACE, 1984).

Piling: A group of piles (USACE, 1984).

Plain, coastal: See *coastal plain* (USACE, 1984).

Plainform: The outline or shape of a body of water as determined by the stillwater line (USACE, 1984).

Point: The extreme end of a cape; the outer end of any land area protruding into the water, usually less prominent than a cape (USACE, 1984).

Port: A place where vessels may discharge or receive cargo; it may be the entire harbor, including its approaches and anchorages, or only the commercial part of a harbor where quays, wharves, facilities for transfer of cargo, docks, and repair shops are situated (USACE, 1984).

Preexisting: Existing before a specified time or event (Morris, 1978).

Profile, beach: The intersection of the ground surface with a vertical plane; may extend from the top of the dune line to the seaward limit of sand movement (USACE, 1984).

Quarrystone: Any stone processed from a quarry (USACE, 1984).

Recession (of a beach): (1) A continuing landward movement of the shoreline. (2) A net landward movement of the shoreline over a specified time (USACE, 1984).

Reflected wave: That part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface (USACE, 1984).

Refraction (of water waves): (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed; the part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents. (USACE, 1984)

Retreat: To move in a landward direction away from an eroding streambank or shoreline.

Revetment: A facing of stone, concrete, etc., built to protect a scarp, embankment, or shore structure against erosion by wave action or currents (USACE, 1984).

Riparian: Pertaining to the banks of a body of water (USACE, 1984).

Riparian area: Vegetated ecosystems along a waterbody through which energy, materials, and water pass. Riparian areas characteristically have a high water table and are subject to periodic flooding and influence from the adjacent waterbody. These systems encompass wetlands, uplands, or some combination of these two land forms; they will not in all cases have all of the characteristics necessary for them to be classified as wetlands. (Mitsch and Gosselink, 1986; Lowrance et al., 1988)

Riprap: A protective layer or facing of quarrystone, usually well graded within wide size limit, randomly placed to prevent erosion, scour, or sloughing of an embankment of bluff; also the stone so used. The quarrystone is placed in a layer at least twice the thickness of the 50 percent size, or 1.25 times the thickness of the largest size stone in the gradation.

Rubble: (1) Loose, angular, waterworn stones along a beach. (2) Rough, irregular fragments of broken rock. (USACE, 1984)

Rubble-mound structure: A mound of randomly-shaped and randomly-placed stones protected with a cover layer of selected stones or specially shaped concrete armor units. (Armor units in a primary cover layer may be placed in an orderly manner or dumped at random.) (USACE, 1984)

Run-of-the-river dam: Usually a low dam with small hydraulic head, limited storage area, short detention time, and no positive control over lake storage.

Runup: The rush of water up a structure or beach on the breaking of a wave. Also *uprush*, *swash*. The amount of runup is the vertical height above still-water level to which the rush of water reaches. (USACE, 1984)

Salt marsh: A marsh periodically flooded by salt water (USACE, 1984).

Sand: See *soil classification* (USACE, 1984).

Sandbar: (1) See *bar*. (2) In a river, a ridge of sand built up to or near the surface by river currents. (USACE, 1984)

Sand bypassing: See *bypassing, sand* (USACE, 1984).

Scour: Removal of underwater material by waves and currents, especially at the base or toe of a shore structure (USACE, 1984).

Seawall: A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action (USACE, 1984).

Shoal (noun): A detached elevation of the sea bottom, composed of any material except rock or coral, which may endanger surface navigation (USACE, 1984).

Shoal (verb): (1) To become shallow gradually. (2) To cause to become shallow. (3) To proceed from a greater to a lesser depth of water. (USACE, 1984)

Shore: The narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. A shore of unconsolidated material is usually called a *beach.* (USACE, 1984)

Shoreface: The narrow zone seaward from the low tide *shoreline*, covered by water, over which the beach sands and gravels actively oscillate with changing wave conditions (USACE, 1984).

Shoreline: The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with shore or beach). The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line. (USACE, 1984)

Silt: See *soil classification* (USACE, 1984).

Slip: A berthing space between two piers (USACE, 2984).

Slope: The degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25 or 1 on 25, indicating 1 unit vertical rise in 25 units of horizontal distance, or in a decimal fraction (0.04); degrees (2° 18′), or percent (4 percent). (USACE, 1984)

Soil classification (size): An arbitrary division of a continuous scale of grain sizes such that each scale unit or grade may serve as a convenient class interval for conducting the analysis or for expressing the results of an analysis (USACE, 1984).

Spit: A small point of land or a narrow shoal projecting into a body of water from the shore (USACE, 1984).

Splash zone: Area along the shoreline above the zone of influence of waves and tides that is still wetted by the spray from breaking waves.

Storage dam: Typically a high dam with large hydraulic head, long detention time, and positive control over the volume of water released from the impoundment.

Stream: (1) A course of water flowing along a bed in the earth. (2) A current in the sea formed by wind action, water density differences, etc.; e.g., the Gulf Stream. See also *current, stream.* (USACE, 1984)

Suspended load: (1) The material moving in suspension in a fluid, kept up by the upward components of the turbulent currents or by colloidal suspension. (2) The material collected in or computed from samples collected with a suspended load sampler. Where it is necessary to distinguish between the two meanings given above, the first one may be called the "true suspended load." (USACE, 1984)

Tailwater: Channel or stream below a dam (Walberg et al., 1981).

Tidal flats: Marshy or muddy land areas that are covered and uncovered by the rise and fall of the tide (USACE, 1984).

Tidal inlet: (1) A natural inlet maintained by tidal flow. (2) Loosely, an inlet in which the tide ebbs and flows. Also *tidal outlet*. (USACE, 1984)

Tidal period: The interval of time between two consecutive, like phases of the tide (USACE, 1984).

Tidal range: The difference in height between consecutive high and low (or higher high and lower low) waters (USACE, 1984).

Tide: The periodic rising and falling of the water that results from gravitational attraction of the Moon and Sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as *tidal current*, reserving the name *tide* for the vertical movement. (USACE, 1984)

Topography: The configuration of a surface, including its relief and the positions of its streams, roads, building, etc. (USACE, 1984).

Tropical storm: A tropical cyclone with maximum winds of less than 34 meters per second (75 miles per hour). Compare *hurricane*. (USACE, 1984)

Updrift: The direction opposite that of the predominant movement of littoral materials (USACE, 1984).

Upland: Ground elevated above the lowlands along rivers or between hills (Merriam-Webster, 1991).

Waterline: A juncture of land and sea. This line migrates, changing with the tide or other fluctuation in the water level. Where waves are present on the beach, this line is also known as the limit of backrush. (Approximately, the intersection of the land with the still-water level.) (USACE, 1984)

Wave: A ridge, deformation, or undulation of the surface of a liquid (USACE, 1984).

Wave height: The vertical distance between a crest and the preceding trough (USACE, 1984).

Wave period: The time required for a wave crest to traverse a distance equal to one wavelength. The time required for two successive wave crests to pass a fixed point. (USACE, 1984)

Wave, reflected: That part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface (USACE, 1984).

Wetlands: Those areas that are inundated or saturated by surface water or ground water at a frequency and duration to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions; wetlands generally include swamps, marshes, bogs, and similar areas. (This definition is consistent with the Federal definition at 40 CFR 230.3, promulgated December 24, 1980. As amendments are made to the wetland definition, they will be considered applicable to this guidance.)

Wind waves: (1) Waves being formed and built up by the wind. (2) Loosely, any waves generated by wind. (USACE, 1984)

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